DEEP HOLE DRILLING IN HIGH SPEED STEEL USING ELECTROCHEMICAL MACHINING

by

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INDIAN INSTITUTE OF TECHNOLOGY KANPUR

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CERTIFICATE

This is to certify that the work contained in the thesis entitled "***Deep Hole Drilling in High Speed Steel Using Electrochemical Machining*** ", has been carried out by Santosh Sharma under our supervision and that this work has not been submitted elsewhere for a degree.

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Abstract

To cater the need of technologically advanced industries like aerospace, nuclear, automobile industries etc. rapid progress has been made in the field of materials science to evolve a material having superior property in terms of strength, hardness and toughness. To machine such 'hard to machine' alloys by conventional machining methods, the tool must be superior in properties as compared to work material. In near future, the chances of development of such high strength tool material, seems remote. Hence, to meet such challenges, a different class of machining processes (non-traditional machining) has been developed.

For many years, Electrochemical Machining (ECM) has been known as a highly effective method for such purposes. But development of ECM process as an industrial process has been slow due to lack of dimensional control when NaCl, $NaNO_3$, or acid used as an electrolyte. In the present work machining has been tried out with NaCl electrolyte with small amount of HCl added to that. Time required for machining, metal removal rate have also been studied. Also the profile of the hole have been studied. SEM photograph of the hole produced are also presented.

Nomenclature

MRR	Metal removal rate
MRR_l	Linear Metal Removal Rate
MRR_g	Mass Material Removal Rate
IEG	Inter electrode gap
ECM	Electrochemical machining
STEM	Shaped Tube Electrochemical Machining
ESD	Electro-Stream Drilling
I	Current (Amp)
A	Atomic number of metal. (gm-mol)
z	Valency of metal.
F	Faraday's constant(C)
η	Efficiency of the Electrochemical reaction.
K_{sp}	Solubility product
V	Voltage (V)
K_e	Conductivity of the electrolyte.
ρ	Density of the metal.
t_a	Actual machining time.

Chapter 1

INTRODUCTION

1.1 INTRODUCTION

Shaping of a metallic material mechanically requires a harder tool to scoop out the softer material. As in the aerospace industries and nuclear power industries, the ever increasing development of the high strength, high temperature alloys places extreme demand on the hardness of tool material. These alloys are called as "hard to machine alloys". Conventional machining processes finds its limitation in economically machining of these alloys. Attempts have been made to circumvent the difficulties i.e. by hot machining in which the workpiece is heated so as to reduce the difficulty of cutting, or by development of abrasive method of machining such as ultrasonic machining. These however met with only limited success. The intricacy of the part required and hectic tolerances further accentuates the problem of machining for conventional machining. One such problem faced by the industries is micro hole drilling of high aspect ratio in super-alloys like Inconel. So there is an urgent requirement for alternative machining technique which can find its place in industrial use. In this entire gamut, the non-conventional machining techniques can be a best solution for the above problem.

The non-conventional machining processes are classified into three basic categories that are – mechanical, thermo-mechanical, and electrochemical and chemical processes.

Some positive features of the non-traditional processes are;

(i) Most of the processes are independent of the hardness of the material to be machined.

(ii) Low machining rate but better surface quality of surface produced.

(iii) No heat treatments are necessary after the experiments.

(iv) In the near future it may lead to unmanned machining modules.

Following are some of the non-conventional machining methods;

- Micro-drilling,
- Ultra-Sonic Machining (USM),
- Abrasive Jet Machining (AJM),
- Electro-Discharge machining (EDM),
- Laser Beam Machining (LBM),
- Plasma Arc Machining (PAM),
- Electron Beam Machining (EBM),
- Electro-Chemical machining (ECM),
- Chemical Machining (CHM).

Before selecting a particular process the process capability, economic considerations and properties of the work material should be taken into consideration. EDM and LBM are thermal methods of machining and hence they cause somewhat metallurgical damage to the workpiece, which affects its mechanical properties. EBM and LBM are costly methods and hence applications are limited.

Electrochemical machining, which machines the material by the virtue of Faraday's laws of electrolysis, is a promising technique for such types of machining. ECM is a contact-less machining process. In ECM, a controlled anodic dissolution of the workpiece takes place. ECM offers impressive and long lasting advantages. The anodic dissolution process does not induce mechanical stresses in the metal lattice, nor thermal modification of metallurgical structure. It machines without regard to the hardness of the material being cut and virtually without tool wear. It is just as easy to machine hard alloys as it is soft material. In certain alloys, however the fatigue property may be lowered, but the fatigue strength can be restored by vapor blasting or shot peening the machined surface. H_2 is liberated at the cathode hence there are no incidences of embrittlement of the workpiece in conventional ECM. ECM machines the material without work hardening, barring and smearing. It also does the machining at ambient

temperature, which avoids the possibility of metallurgical damage to the workpiece due to heating. Because of all these advantages ECM can be used for preparing tensile specimen.

The present work is an effort towards making of a deep hole so that in near future it can be employed for micro-hole drilling.

There are basically two techniques of micro-hole drilling by electrochemical machining.

1 ***Electro-Stream Drilling(ESD);*** it is a special form of the ECM process which employs the negatively charged high velocity stream of acidic electrolyte to achieve anodic dissolution of metal. The tool is a drawn-glass nozzle, one or two thousandth inch smaller than the desired hole size required. The electrolyte is charged with the help of an inserted electrode inside the nozzle. Voltages employed are generally 10 times more than those employed in STEM operations. Holes ranging from 0.2 to 1.0 mm can be drilled with diameter to depth ratio 50:1 can be made in conductive metals. But the excessive corrosive nature of the electrolyte may shorten the life of the equipment.

2 ***Shaped Tube Electrochemical Drilling (STEM)***; is a another version of the ECM process used for making small deep holes. The electrode is a hollow metal tube, which is coated from outside to avoid any sort of stray machining. The metal dissolution takes place by controlled anodic dissolution of the workpiece. Holes of diameter 0.5 to 6.4 mm can be drilled with aspect ratio of 300:1. The gap is generally smaller than previous case, hence the voltage required is smaller.

ECM has its own inadequacy of being applicable to conductive parts only. The corrosion of the accessories parts is big problem to this process. It is not possible to produce sharp edges by this process but in some cases this may be advantageous for producing no burrs. The preparation of tool for particular job is the big problem of ECM, because exactly the same replica of cathode can not be produced at anode. But

these initial tooling cost can be gained quickly through the high efficiency of the ECM process and the virtual lack of any tool wear if the replication of the part to be machined is high. Further the electrochemical behavior of the metal with different electrolyte in different conditions complicates the process, hence the process has not been exploited to the fullest extent.

Principle of Electrochemical Machining

Any ECM process can be divided into one of two categories; Hole making or Die sinking. Die sinking involves machining over a large contoured area and thus require high currents and electrolyte flow rates. While in hole making the machining takes place in a small area below the tip of tool.

ECM is a highly irreversible process. Electrochemical drilling employs the Faraday's law of Electrolysis for the making of the hole in metals. The workpiece is dissolved atom by atom by the controlled anodic dissolution. According to Faraday's law the passage of each Faraday of electrical charge results in the dissolution of an equivalent weight of metal, assuming that all of the current passed at anode is consumed by metal dissolution (no side reaction). Faraday's law states that amount of metal dissolved is ;

1. Directly proportional to the amount of current flowing through the gap,
2. Inversely proportional to the valency state of the metal dissolution.

The theoretical rate of material dissolution is given by;

$$MRR = \frac{AI}{zF} \quad gm/s \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.1)$$

Where A-Atomic number of the metal under consideration,
I-current flowing through the gap,
z- valency state of the metal dissolution,
F-Faraday's constant (96500 Coulombs).

But in actual practice the amount of metal dissolution of metal deviates from the calculated theoretical removal rates. This is mainly due to the fact that exact valence state of the metal dissolution is not clearly predictable. For example the apparent valency of copper dissolution changes with the mode of dissolution[1]. In case of alloys, Electrochemical Equivalent (A/z) value is to be calculated in order to estimate exact metal dissolution rate. There are two methods for this calculation one is "percentage by weight method" and "Superposition of charge method"[1].

The workpiece is made anode while the properly shaped tool is made cathode. For making of the deep hole with high aspect ratio the tool used should be wire like electrode of smaller diameter than the required hole diameter. The electrolyte, which is necessary for completing the electrolytic cell between tool and workpiece, should be pumped through the gap. For this very purpose the hollow electrode is elmployed to facilitate pumping of electrolyte. The schematic diagram of the Electrochemical Drilling process is shown in Fig. 1.1.

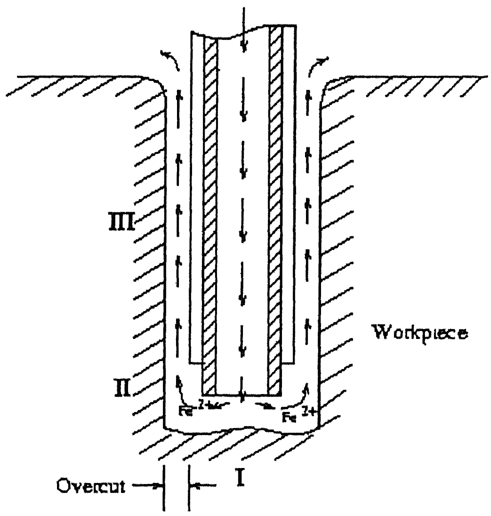


Fig 1.1 The schematic diagram showing phenomenon of Electrochemical Machining.

The other purposes of electrolyte flow are to flush away any reaction products (precipitate) and to reduce the amount of Joule heating. A small gap of the order of 0.1 mm to 0.5 mm is maintained between the electrode and workpiece. A DC voltage of the order of 5 - 30V is required for ECM. During the ECM process, metal removal from the anode produces, an increase in the gap distance which causes a decrease in current; if the situation is not corrected, the current will fall to a point where machining stops. Consequently, either the anodic workpiece or the cathodic tool is moved by the mechanical drive system to maintain the desired gap. If this feed rate is too high for a given metal removal rate, a short circuit between the tool and the workpiece is possible, and the catastrophic damage to the tool due to spark erosion thermal melting and, welding and metal tearing are possible results. To prevent this costly damage, most ECM machine are protected by sensing device which detect increasing rates of current or transient in the applied voltage when the gap closes beyond a certain specified safe distance, thus blocking the current. There is no mechanical contact between the tool and workpiece. Under this conditions, a shape roughly complimentary to that of the cathode, will be produced. As the hole is being made, tool inserts into the hole; it may cause stray machining. Hence to obviate stray machining the tool should be coated from outside.

Within most of the values of the feed rates and current density, the system rapidly reaches an equilibrium or steady state gap distance due to the balance of the opposing processes of the feed rate which tends to narrow the gap and current density which tends to widen the gap. Nevertheless, there are some incidences of mismatching of feed rate and metal removal rate (MRR_l), which is due to variation in the net material removal rate. The reasons for this are:

1 Changes in conductivity due to accumulation of sludge, heating of the electrolyte, and evolution of H_2 gas.
2 Error in the assumption of valence state of dissolution and hence the MRR.
3 Solubility product (K_{sp}) of hydroxide changes with temeparature.

The electrolyte, which is in general use for hole making ECM purposes, is 10% NaCl solution. The electrochemical reaction which are taking place during the machining are:

In acidic solution:

At anode:

$Fe \leftrightarrow Fe^{2+} + 2e^-$ $E_{Fe/Fe^{2+}} = -0.44V$ (1.1)

$Fe \leftrightarrow Fe^{3+} + 3e^-$ $E_{Fe/Fe^{3+}} = -0.04V$ (1.2)

At cathode:

$2H^+ + 2e^- \leftrightarrow H_2 \uparrow$ (1.3)

Since oxidation potential of the reaction 1.1 is more than reaction 1.2 hence former one is the most favorable reaction. Reaction 1.3 will increase the pH of the original solution somewhat. The extent of increase is also a function of flow rate of electrolyte.

The anodic and cathodic products will interact with dissolved oxygen, to form loose flocculent hydroxides, which being precipitate well away from iron.

$$Fe^{2+} + 2(OH^-) \rightarrow Fe(OH)_2 \quad (1.4)$$

The Ksp value of the above reaction is given by;

$$Ksp = [Fe^{++}] \times [OH^-]^2 \quad (1.5)$$

Thus by making the solution more acidic (i.e. by decreasing the OH^- ion concentration) and by flushing the metal ions it is possible to decrease the chances of precipitation.

With salt solutions, the volume of metal hydroxides or metal hydrate is much higher, this may cause difficulties in flushing. Hence the addition of small amount of acid to salt

solutions have been suggested which lessen the chances of precipitation. The voltage should be sufficient to overcome various drops, which are taking place during process. The various drops that are taking place in ECM operations are;

- Resistance of the gap,
- Concentration over-potential,
- Activation over-potential at anode and cathode,
- Decomposition over-potentials.

1.2 Literature Survey

ECM works on the principle of Faraday's law of Electrolysis, metal removed is directly proportional to the amount of current passed through the cell. The process of passivation complicates the phenomenon. Passivation depends upon nature of the electrolyte used and operating conditions of the process like voltage, current and pH etc. Hence the use of proper electrolyte is a very crucial step in making a successful micro-hole with good tolerances.

ECM process is generally considered as a high rate anodic corrosion process. It is generally agreed that metal dissolution takes place in the trans-passive region. Most of the initial attempts have been made with NaCl electrolyte, but it produces lot of the over-cut which makes it less advantageous. After finding the advantages of the $NaClO_3$ electrolyte the studies have been concentrated over that electrolyte.

From Fig 1.1 it is clear that to decrease the extent of over-cut region II and III should be in the passive region while I should be in the trans-passive range. The sideways regions II and III are under low potential due to larger inter electrode gap, there exist a passive region, while in the frontal region there exist a trans-passive region due to lower gap. This type of situation can be attained in $NaClO_3$ and $NaNO_3$ electrolytes. These types of optimal voltage distribution can be secured through proper choice of voltage, electrolyte concentration, temperature and flow rate. In the case of NaCl electrolyte this

type of condition is not maintained which is the very reason for poor machining performance.[2]

Hoare and LaBoda[3] confirmed that electrochemical dissolution takes place in the trans-passive region. They have explained that $NaClO_3$ electrolyte forms a potential dependant anodic film on the metal surface, which gives a good control of the geometry and dimensions. The oxidizing power of the ClO_3^- ion is quite high which promote the formation of the passivating films upon the surface of metal. They found that as the potential is increased the FeOOH film (which is strongly passivating in nature) converts to soluble Fe $(ClO_3)_3.3OH$ compound. Thus at the tip where a small gap is maintained exists a trans-passive region and hence a very thin shining and porous film exist, which causes high dissolution at that spot, while at the sideways where there exist a passive region virtually no machining takes place in sideways. This is the very reason that the low over-cuts are achieved while using $NaClO_3$ electrolyte. They have stated in their previous paper that HCl produces large over-cut. Also the profile of anode shape after machining was not predictable which makes the tool design process tedious and expensive.

Madhav et al.[4] confirmed the presence of a very thin oxide layer on the metal surface in case of $NaClO_3$ electrolyte. In their paper they have investigated the anodic dissolution of Ni-200 in NaCl and NaClO3 electrolyte solution and the mixture of the two. They have stated that in the transpasssive region the passivating film may break down locally or may undergo a chemical change favoring uniform dissolution. The former case leads to pitting of surface, which is the case with NaCl, while with $NaClO_3$ a steady state film formation takes place, which ensures electropolishing of the surface. From their experiments they have deducted that current efficiency in NaCl solution was independent of current density. No active region was observed in case of $NaClO_3$ electrolyte. Also in lower transpassive potential there is generation O_2 gas, while at somewhat higher potentials there is a metal dissolution. With the presence of chloride ions in chlorates the dissolution efficiency of exceeded 100 % due to synergistic effect.

Initial attempts have been made with NaCl electrolyte using insulated tool for making hole. But Chryssolouris and Wollowitz[5] reported in their paper that surface roughnesses are produced when NaCl electrolyte is used with coated electrode. They have stated that this is due to relative low current density in the sideways of the cathode tool. With $NaClO_3$ electrolyte they have conducted few experiments with 316 stainless steel and confirmed that surface finish and integrity improves which is far superior to that in NaCl electrolyte. Also the degree of taper and over-cut increases with voltage and electrolyte concentration and machining time.

Hoare[6] studied the effect of few electrolytes like NaCl, $NaClO_3$, $NaNO_3$ and $Na_2Cr_2O_3$ on the passivating layer formation on the surface of soft iron. They have found that chloride ions are so effective that they dissolve the oxide film, while chromate ions protects this oxide films even at higher potential. He has produced a polarization curve for these electrolytes this is shown in Fig 1.2. From the figure it is evident that there is a sharp transition from passive to trans-passive region in case of NaClO3 electrolyte which favors efficient machining.

Brook and Iqpal [7] have conducted experiments from which they have shown that $NaClO_3$ has a lower throwing power than NaCl. In ECM, stray current is reduced at low value of throwing power and becomes negligible if throwing power becomes almost nil.

Pandey et al.[8] reported that the hole accuracy improves with the relative slow rotation between the tool and the workpiece. They have proved that with the slight rotation of electrode electrolyte flow rate increases, which avoid any more temperature rise in the inter electrode gap. Also the bubbles which forms during process would be smaller than doing with the non-rotating electrodes.

Ippolite et al.[9] presented a paper in which they have shown that inter electrode gap no longer behaves as a conductor in accordance with the ohm's law as its conductivity changes is also a function of current passing through it. This is due to the fact that at cathode there is H_2 evolution and the formation of reaction products, which

are current dependent. They have devised a formula in which they have shown that gap resistivity is little influenced by flow rate to current ratio, but most affected by voltage to current ratio.

The feed rate is inversely proportional to the inter electrode gap[10], lower inter electrode gap decreases the amount of over-cut. Hence it is desirable to keep the feed rates on the higher side to produce lower over-cuts and to keep the productivity as high as possible. But Larsson and Baxter[11] in their paper presented that tool damages occur at high feed rates by unwanted sparking in ECM. The cause of sparking in ECM is not clear. If for some reason the tool does approach the work, the current density should rise and causes the work surface to recede at a faster rate. But in practice there are limitations. They have found that in practice there are tool damages by unwanted sparks above a certain threshold value of feed rate. Also they have found that the rate of sparking increases with increase in the feed rate but decreases with the increase in the applied voltage.

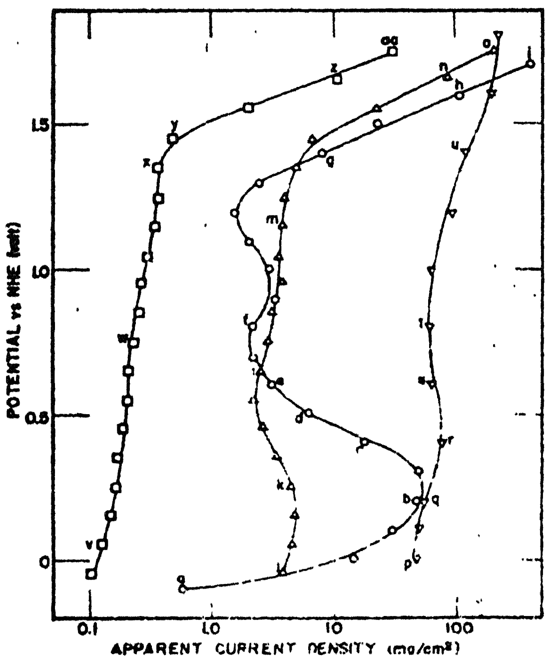


Fig 1.2 Polarisation curves of iron electrodes in electrolyte of $NaClO_3$ o;, $NaNO_3$ Δ; NaCl ∇; $Na_2Cr_2O_3$ □.[6]

1.3 Objective

Making a through micro hole of very high aspect ratio is presently in demand to cater the need of cooling in turbine blades. There are only 2 to 3 manufacturers worldwide for micro hole drilling purposes by ECM process. So the present work has been an effort towards making of micro hole in Inconel alloys indigenously. The main objective of present work has been;

- Fabrication of a STEM process for successful hole drilling of electrically conducting material.

- To study the effect of process parameters (i.e. feed rate and voltage) on and time of machining and on the amount of taper produced.

- To find out the feasibility of using this method for drilling holes in Inconel.

Chapter 2

EXPERIMENT

Making of a suitable set-up for the electrochemical drilling was the major objective of the work. The present chapter describes (1) Electrochemical machining (2) Electrode feed Mechanism (3) Electrolyte flow system (4) Electrode (5) Sample preparation and (6) Experimentation. Also this chapter include the feed rate calculations for the tool. The electrode feed mechanism and feed controller circuit is added to the existing set up which was made by Sastry[12].

2.1 Electrochemical Drilling Machine

The assembled experimental set-up for the electrochemical drilling purpose is showing Fig 2.1. The parts that come in direct contact with the electrolyte should be made up of corrosive-resistant material. For that purpose epoxy resins, glass fibers, perspex or PVC have been suggested. Also during process lot of the fumes are generated to avoid that harmful fumes, the chamber should be sealed properly. The set-up can be divided into following parts.

1. Work holding device,
2. Electrode feed mechanism,
3. Electrolyte flow system,
4. Power supply.

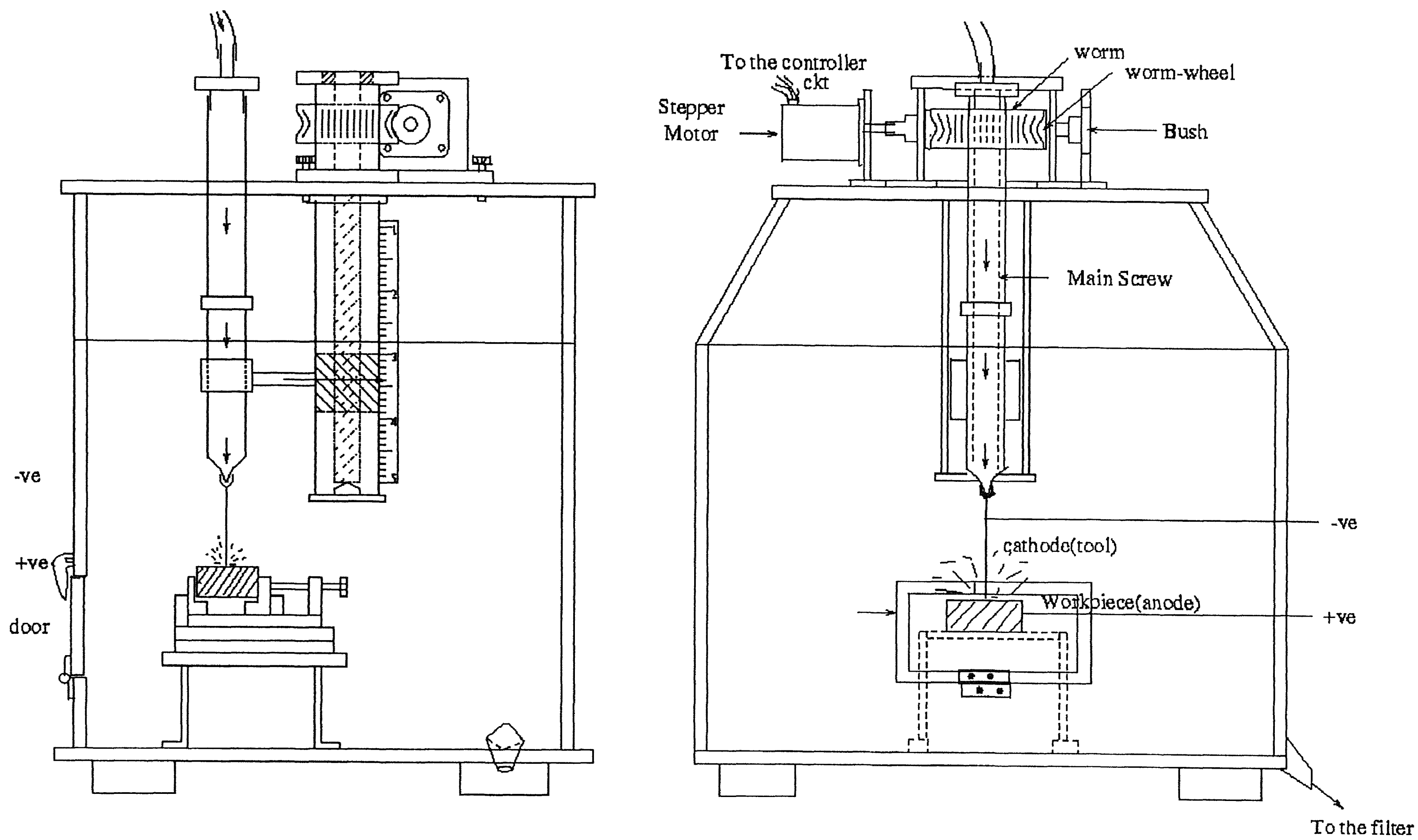


Fig 2.1 The schematic diagram of the Electrochemical Machine[12].

2.1.1 Work Holding Device

The workpiece-mounting fixture consists of Work Vice and Screw Jack.

A vice is required for holding workpiece and a screw jack is needed for imparting vertical movement to the workpiece. Both the work vice and screw jack are made of Perspex. Perspex is a good insulating material and is corrosion resistant. The surface of the Screw Jack is made flat to ensure that the surface of workpiece is perpendicular to the cathode tool. The Screw Jack is fixed to the bottom of machining chamber; the vice is fixed over the car Jack. Figures of the Car Jack and vice are shown in Fig 2.2 and Fig 2.3 respectively.

2.1.2 Electrode Feed Mechanism

The electrode feed mechanism consist of (1) Screw and Worm wheel arrangement (2) Stepper Motor (3) Stepper Motor Controller Circuit.

2.1.2.1 Screw and Worm wheel arrangement

The electrode is attached to the tool Main screw as shown on Figure 2.1. The main screw is having a pitch of 1.5 mm which can be driven by worm-wheel arrangement. The worm wheel has a ratio of 1:36. Worm is driven by stepper motor. And the necessary signals to the stepper motor are provided through stepper motor controller circuit. Feed rates varying from 0.277 mm/min to 1.5 mm/min can be achieved through this arrangement.

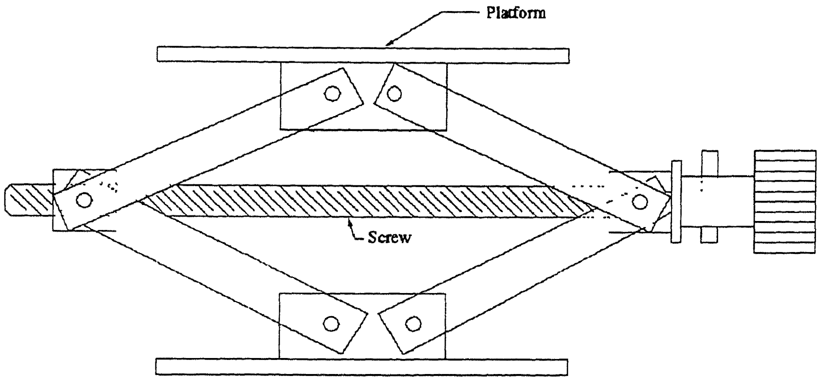


Fig 2.2 Screw Jack for holding the vice.

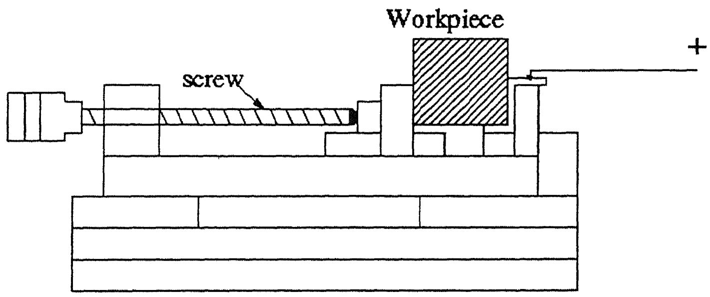


Fig 2.3 Vice for fixing the workpiece.

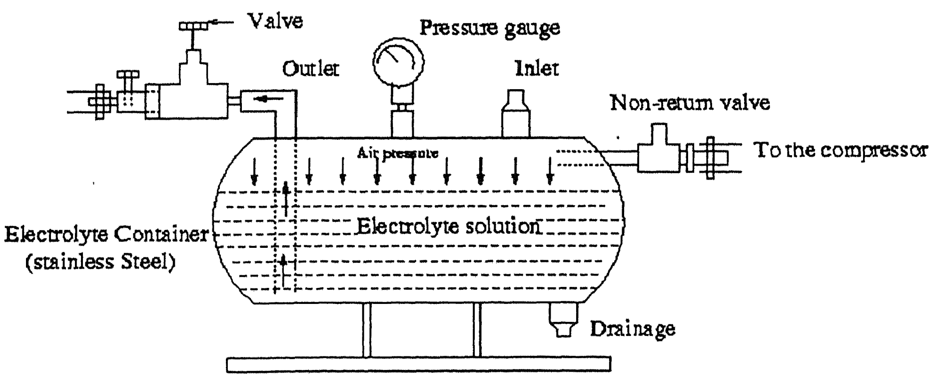


Fig 2.4 Electrloyte Chamber.

2.1.2.2 Stepper Motor

The feed to the tool is provided through stepping motor. The control and drive mechanisms are built externally. The motor moves in step size of 1.8°, so that 200 steps are required for one complete rotation.

The necessary parts of a stepper motor are a rotor of magnetic material, having many numbers of poles and a salient stator with corresponding number of poles. Sequential switching of supply to the two phases of the motor causes the stepping action. Rotor and stator are mutually displaced by half a pitch. The stator is housed in a steel body and rotor is mounted on sealed bell bearing, which assures permanent lubrication. The holding torque of this motor is rated at 2 kg-cm, which is sufficient for our purpose. These motors are specified to work at 12v. The motor can be made to rotate in either direction. These features make it useful for the automatic control of system. The stepping motor can be programmed in three parameters; a) Direction, b) Speed, c) Number of steps.

2.1.2.3 Stepper Motor Controller Circuit

As mentioned previously the driver circuit, for driving stepping motor are built externally. It is an essential to maintain a small inter electrode gap during machining. A small inter electrode gap leads to lesser IR drop at the inter electrode gap, hence a higher MRR can be achieved for a given operating voltages. This requires precision monitoring the cathode motion to avoid any short circuiting by sensing the current flowing through the main circuit.

The circuit essentially consists of a controller oscillator, two phase clock generator forward and reverse control and driver stage. Controlled oscillator is designed using timer IC555 to give a clock signal of 10Hz to 20kHz.

Two-phase clock generator also called as bi-directional logic sequence. BLS is built with sequentially using JK-flip –flop or OR invert (AOI) gates. It controls the

excitation of winding sequentially, responding to the clock signal generated by 555 oscillator. This is capable of controlling the motor excitation in both directions, clockwise and anti-clockwise. The clock and direction are the input to this circuit. The signals generated by this circuit are buffered and used as input to the Mosfets.

The driver circuit is built with the power MOSFETS. Use of power MOSFETS makes the design of drive board very simple and adaptive for a wide range of motor with different torque ratings. Jumpers are connected to change the direction of movement.

The electrical circuit for current sensing in the main circuit is shown in Fig 3.4. The detailed circuit diagram of the current sensing circuit is shown in Fig. Al in Appendix. The electrical circuit is made up of a resistance of suitable value (in our case 0.5Ω) placed in series of the main circuit. Output from the current sensing circuit is fed to the stepper motor controller circuit. If current flowing through resistor goes beyond an acceptable limit (for 0.5Ω, 4 A and for 0.9, Ω 6 A) then it gives the proper feedback to the controller circuit and which in turn changes the direction of movement of the stepper motor.

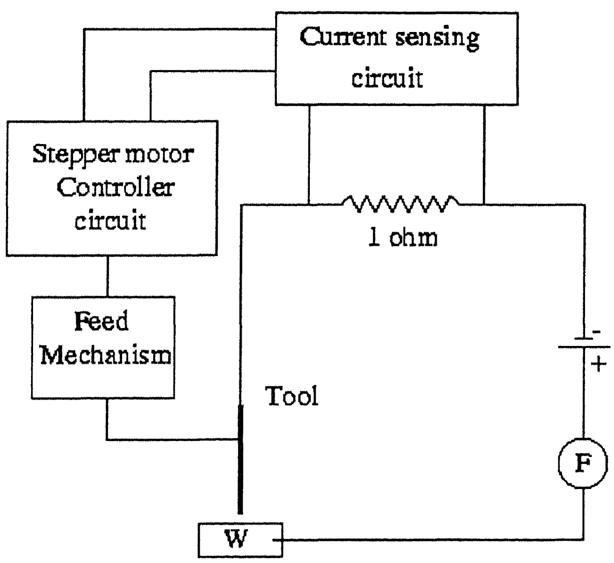


Fig 2.4 Electrical Circuit for avoiding short circuiting in ECM.

2.1.3 Electrolyte Flow System

The electrolytes used for Electrochemical Machining purposes are generally corrosive in nature. Hence use of metal avoided. Also proper sealing of the system is made at the junctions to avoid any leakage of the electrolyte. The pipes used for electrolyte flow should sustain the high pressure (40-50 lbs/inch^2) generated during pumping the electrolyte.

2.1.3.1 Electrolytic Chamber

Electrolytes normally encountered in ECM operations, are corrosive in nature. Hence for pumping purposes so mean should be used which are resistant to these electrolytes.

Initially electrolyte was pumped with low power pump. The main problem with those pumps was excessive corrosion and also the flow rate achieved was not enough to flush away the reaction products, which are accumulated in the gap during machining.

Later a stainless steel chamber shown in Fig 2.5 was used for electrolyte pumping. Air necessary to pump electrolyte is made available through a compressor. A pressure gauge is connected to the chamber for checking and controlling flow rate of the electrolyte. A non-return valve is connected to the container to avoid any sudden release of pressure. The outlet of electrolyte chamber is connected to the electrode through proper channel. With the use of electrolytic chamber the flow rates of electrolyte can be controlled.

2.1.3.2 Electrolyte Reservoir

Electrolytes after machining is filtered and collected in a bucket. The conductivity and pH of the electrolyte is checked.

2.1.4 Power Supply

The amount of over-cut increases with voltage which is unfavorable. Hence the voltages are generally kept in the range of 5-25 volts and in some extreme cases at 30V. In ECM operation the voltage used are in the range of 5 to 30 volts. The three-phase voltage is converted to DC voltage by means of a step down transformer and rectifier. The specification of constant power supply used in ECM is as follows:

A.E. constant current rectifier

Input voltage –230V

Output voltage-0 to 150

Phase –single

Output current – 20 ± 0.5 V

Capacity-3.9KVA.

2.2 Machining Chamber

The chamber is made of Perspex of dimension 400mm X 250mm X 300mm. The machining chamber houses the work holding device, the electrode holding arrangement. The chamber is necessary to protect from splashing that occurs during machining. The chamber is provided with outlet at the bottom to facilitate used electrolyte disposal. The schematic diagram of machining chamber is shown in figure 2.1.

2.3 Electrode

High electrical conductivity of the tool material are the main requirements. Two electrodes were used.

(i) *Cu tool with bit at the tip:*

A Cu tube (outer diameter 1.75 mm and internal diameter 0.677 mm) has been taken and at the tip a small bit of 3 mm diameter has been soldered as shown in Fig 2.6a. The bit type of tool allows enough machining so that electrolyte after machining can

remove easily[12]. But trails with these tool was observed with large over-cut. To minimize the extent of overcut bit of very accurate dimension should be chosen.

(ii) *Hypodermic Syringe:*

The second tool, which was tried out, was hypodermic syringe. It is made of stainless steel, which is having more resistance than Cu. Thus for a given supply voltage, voltage available at anode is lesser which results in a smaller inter electrode gap. This might be the reason behind frequent sparking incidences with this electrode even at the lower feed rates.

Later an electrode as shown in Fig 2.6b is used. The cathode tool is made up of hollow copper tube (internal diameter 0.677 mm and outer diameter 1.75 mm). To avoid stray machining the tool is coated with insulating layer of Perspex. A small amount portion at the lower end of the electrode is kept bare for pursuing frontal machining[14]. The tool fixture must be rigid enough to avoid vibration or deflection under the high hydraulic forces. The tool must be perfectly straight; otherwise it will result in unnecessary short-circuiting during machining.

A solution of Perspex dissolved in chloroform is used for coating purpose. Being an insulator the perspex coating abstain the tool from stray machining. The electrodes are straightened with the help of suitable dies. The electrode is soldered to the head of the syringe. Prior to coating the tool, the outer surface is roughened with the help of emery paper. Then the surface of tool is coated with tender care. To ensure insulation coating the coating has been done four times. After coating the conductivity is checked with multi-meter.

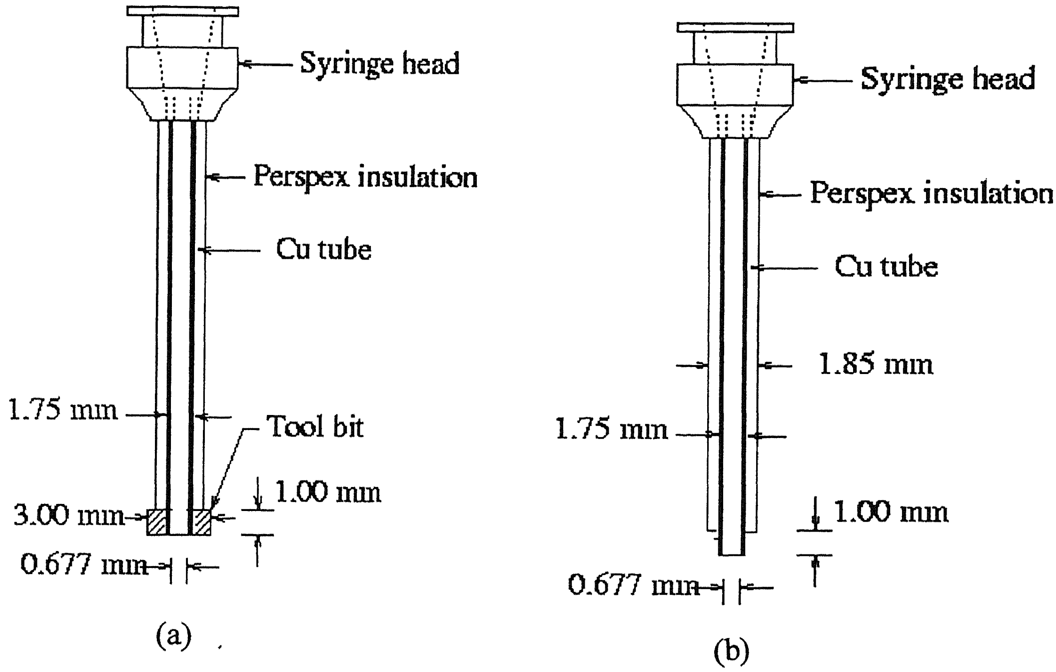


Fig 2.6 Electrodes used for ECM drilling.

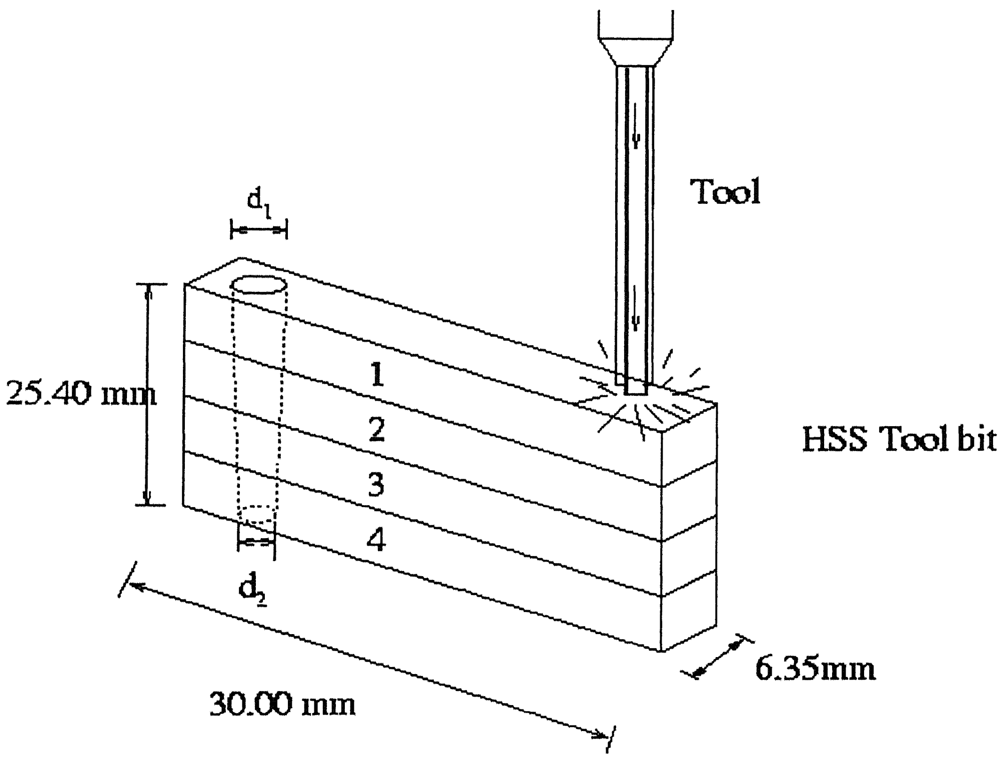


Fig 2.7 Composite workpiece.

2.4 Sample Preparation

Before going for the Inconel machining, the trials have been conducted on HSS tool bit. The composition of HSS is as; tungsten-18%, Chromium-4%, Vanadium-1%, Carbon-0.75% and the remaining iron. The tools are of 6.35 mm X 6.35 mm cross section. Such four samples are stacked and soldered as shown in Figure 2.7. This type of strategy is taken to facilitate diameter measurement at many locations.

2.5 Feed Rate Calculations

Before using feed rate as a variable, rough calculations were done to estimate the approximate feed rate required.

According to Faraday's law, the material removal rate is given by;

$$MRR_l = \frac{AI\eta}{zF\rho Area} \quad \text{..........................} (2.1)$$

Where,

MRR_l - Linear metal removal rate.

A- Atomic weight of the metal under consideration,

I- current flowing through IEG (Amp),

z- valency of the metal

F- Faraday's constant (96500 Coulombs),

ρ- Density of the metal under consideration (gm/cm^3),

Area- Area of the hole produced (cm^2),

η- Efficiency of electrochemical dissolution.

Which may be defined as the efficiency of the current in removing metal from the workpiece.

Initial experimentation were done on HSS tool bit. Since HSS is an alloy, (A/z) value is to be calculated for estimating the metal removal rate. For this purpose percentage by charge method was employed.

$$\left(\frac{A}{z}\right)_{HSS} = \frac{1}{100}\left\{\left(\frac{A}{z}\right)_{Fe} + \left(\frac{A}{z}\right)_{W} + \left(\frac{A}{z}\right)_{Cr}\right\} \qquad \text{.....................(2.9)}$$

Considering that all other elements in traces.
The value of the (A/z) is found to be 27.65.

In normal ECM drilling processes normal inter electrode gap is 0.1 mm to 0.5 mm[12]. For present calculations we have taken it as 0.5 mm.
The resistance of the gap can be calculated from Ohm's law;

$$R = \frac{IEG}{\kappa_e \times \Pr ojected\ Area\, of\ electrode} \qquad \text{.......................(2.2)}$$

The experimentation was done with NaCl electrolyte of 10% concentration and small amount of HCl is added (1% by weight). While the electrode diameter is 1.75 mm and internal diameter is 0.677 mm is used for machining purpose. With this values the Resistance had been calculated:
R=20.37 Ω.

The applied voltage is assumed at 25 volts. Then current flowing through the gap can be calculated from Ohm's law.

$$I = \frac{V}{R} = 1.227\ amp$$

It is assumed that hole of 3.00 mm is produced.

Substituting the respective values in the equation 2.1; we get,

$$MRR_l = 5.8896 \text{ X } 10^{-4} \text{ cm/s}$$

Hence the feed should be around 0.353 mm/min.

But in this calculations following considerations are not taken into considerations,

-Effect of gas generation at cathode,

-Effect of rise in temperature in IEG,

-Effect of reaction product formation at IEG.

Generation of gas and formation of the reaction product decreases the conductivity of the electrolyte and hinder machining. While increase in temperature increases the conductivity and promote the metal removal rate. But as the gap decreases the amount of current flowing through the gap increases which in turn increases the metal removal rate.

Taking into considerations all these factors, the feed rate range of the order of 0.277 mm/min to 1.5 mm/min has been devised. A worm wheel of the ratio of 1:36 ratio is employed for this purpose.

2.6 Design of Experiments

2.6.1 Theory

In design of experiments, the investigator organizes consecutive small series of trials, in each of which all the factors are simultaneously varied according to definite rules. The design of experiments is the procedure for selecting the number of trials and conditions for running them, essential and sufficient for solving a problem that has been set with the required precision. The following features are of great importance:

- Striving to minimize the total number of trials,
- The simultaneous variation of all the variables determining the process according to special rules,
- The selection of a clear-cut strategy permitting the experimenter to make substantiated decision after each series of trials of experiments.

Block diagram of the experimental system of studies in Figure 2.8.

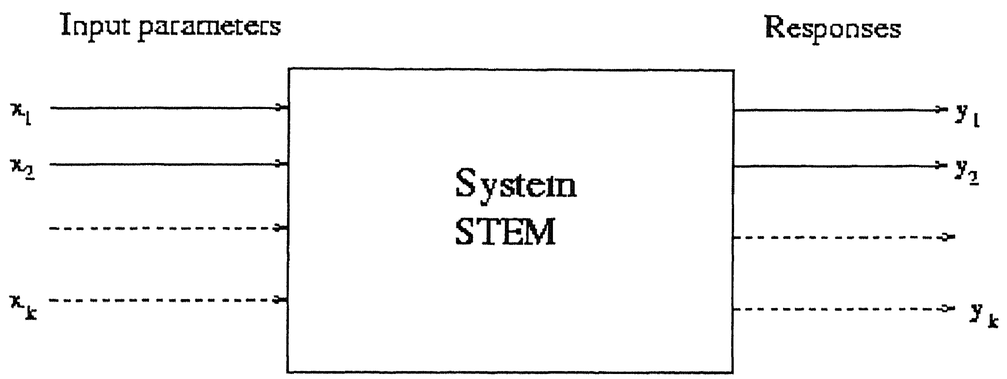


Fig 2.8 Block diagram of the experimental system of studies

The arrows on the right show the numerical characteristic of the goals of investigation and they are called responses (yields). The variables that influence the behavior of the system responses are called factors, and they are input parameters shown on the left side in Figure 2.7.

If all the input parameters represent quantitative variables then the yields (or responses) can be represented as a function of the levels of the variables.

$$y = \phi\,(x_1, x_2, \ldots x_n) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.3)$$

The function ϕ is called the response surface. In the absence of knowledge of mathematical form of ϕ, it can be approximated by a polynomial in the variable of x.
To obtain the idea of interaction and higher order effect, second order design are preferred, such quadratic type of design are used when responses are not expected to be linear and the design is needed to yield estimate of the curvature aspect of each response. The general form of a quadratic (second-degree) polynomial in two x-variables is as follows

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 \;\ldots\ldots\ldots (2.4)$$

Central composite rotatable design is originated to fit second order response surfaces. To explain the concept of rotatibility, let the point (0,0,...0) represents the center of the region in which y and x are under investigation. Let y be the estimate response at a point on the surface as given by equation given below.

$$y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i<j} b_{ij} x_i x_j \;\ldots\ldots\ldots\ldots\ldots (2.5)$$

In rotatable design, the standard error is same for all the points that are at same distance from the center of the region.

2.6.2 Design of Experiments for STEM

To evaluate the effect of feed rate and voltage on material removal rate, time of machining and diameter of hole produced, central composite rotatable design was selected. The design for two x-variables is shown in Table 2.1.

The preliminary step in planning the experiments is setting maximum and minimum values of variables namely operating voltage and tool feed rate. For that

purpose, a few trial experiments have been conducted to check the feasibility of the machining.

Operating Voltage

From the literature it was found that ECM employs voltages ranging from 4 to 30 volts[13]. But when experiments were conducted at 5V and 10V with lowest possible feed rate of 0.277 mm/min, successful machining was not possible. Hence, the voltage range is set from 15V to 30V. The value of voltage on the higher side is limited by the chances of short-circuiting.

Tool Feed Rate

The various feed rates ranging from 0.277mm/min to 1.5 mm/min has been tried. It was observed that there was incidences of sparking of electrode after feed rate exceeded 1.25 mm/min. Very lower value of the feed rate is not chosen to minimize the overcut. Hence the feed rate are set in the range of 0.3 to 1.0 mm/min.

HCl Concentration

It was observed that when plain NaCl (10%) was used as an electrolyte then there was formation of inordinate amount of sludge at the inter electrode gap. This increases resistance of the IEG, which ultimately result in decrease in MRR. It poses the problem of short circuiting. Hence a small addition of HCl (1%) is made which is good enough to avoid excessive formation of sludge. The larger values of concentration are avoided to decrease the extent of taper.

Next the relationship between scaled and actual values of the parameters should be set up. The general equation showing their relationship is as follows:

$$\textit{scaled level} = \mathrm{a} + \mathrm{b} \times \textit{actual level} \qquad (2.4)$$

In the design, scale the lowest and highest values of x as –1.414 and +1.414 for two x-variables. For voltage: $V_{min} = 15$ V and $V_{max} = 30$ V.

$$1.414 = a + b \times 30 \tag{2.5}$$

$$-1.414 = a + b \times 15 \tag{2.6}$$

On solving above equations simultaneously, we get a = -4.241 and b = 0.188; hence,

$$x_1 = -4.241 + 0.188V \tag{2.7}$$

Similarly for feed;

$$x_2 = -6.666 + 8.08f \tag{2.8}$$

From equations 2.4 and 2.5 voltage and feed rate corresponding to the scaled levels -1, 0, 1 are determined. The complete conversion table is tabulated in Table 2.3.

Sr. no.	χ_0	χ_1	χ_2	χ_1^2	χ_2^2	$\chi_1\chi_2$
1	1	-1	-1	1	1	1
2	1	1	-1	1	1	-1
3	1	-1	1	1	1	-1
4	1	1	1	1	1	1
5	1	-1.414	0	2	0	0
6	1	1.414	0	2	0	0
7	1	0	-1.414	0	2	0
8	1	0	1.414	0	2	0
9	1	0	0	0	0	0
10	1	0	0	0	0	0
11	1	0	0	0	0	0
12	1	0	0	0	0	0
13	1	0	0	0	0	0

Table 2.1 Central Composite Rotatable design for two factors.

Levels	Voltage (V)	feed (mm/min)
-1.414	15.0	0.3
-1	17.0	0.40
0	22.5	0.65
1	28.0	0.90
1.414	30.0	1.00

Table 2.2 Values of parameters for different levels.

Sr. no.	Order of Expt	Feed rate (mm/min)	Voltage (volts)
1	1	0.40	17.0
2	7	0.40	27.8
3	11	0.90	17
4	6	0.90	27.8
5	10	0.65	15
6	13	0.65	30
7	8	0.3	22.5
8	5	1.00	22.5
9	2	0.65	22.5
10	12	0.65	22.5
11	3	0.65	22.5
12	9	0.65	22.5
13	4	0.65	22.5

Table2.3 Complete conversion table for three variables.

2.7 Experimental Procedure

The experiments were done in randomized manner to avoid any chances of biased results. The electrolyte of 10% NaCl concentration with 1% HCl (by weight) is prepared. pH and conductivity of the electrolyte is measured and noted down. Then the electrolyte is filled in the electrolyte chamber and pressure is applied through the compressor so in the electrolyte chamber the pressure becomes 40-50 lb/inch^2. Prepared workpiece is cleaned and its dried weight is taken in electronic balance. Then it is gripped in vice and proper connections are made to the workpiece and to the tool. An initial gap of 0.3 mm is set with the help of a filler gauge. The perpendicularity of the workpiece surface with the tool-axis is ensured. After ensuring the proper electrolyte flow, power supply and feed to the tool is switched ON. Supply and feed to the tool are stopped for half minute after each 5 minutes of machining. During that period the flow of the electrolyte is continued to facilitate flushing of the reaction product.

Total time required for machining is recorded with the help of a stopwatch. After completion of the experiments the sample is washed with mild spray of water, dried and then weighed. The hole diameter is measured.

For conducting experiments in other condition the same procedure was followed.

Parameters

Following parameters are kept constant during the experimentation;

Average diameter of the electrode:

Before coating = 1.75mm

After coating = 1.85mm.

Length of the tool = 40mm.

Concentration of NaCl = 10% (by wieght)

Concentration of HCl = 1% (by wieght)

Pressure of the electrolyte chamber = 40-50 lbs/inch^2.

Initial gap = 0.3 mm.

Insulation = Perspex

Fig 2.9 Photograph of the STEM set up.

2.8 Measurements after Machining

2.8.1 Weight

The weight of the workpiece is measured using the electronic balance AFCOSET having a least count of 1 mg. The weight of the samples before and after the machining was recorded and material removal rate was measured by weight loss method.

2.8.2 Machined Hole Diameter

After machining is over the samples are parted off and the diameter measurements are done with a travelling microscope. The readings were taken at 10X magnification. The least count of the meter is 0.01 mm.

CHAPTER 3

RESULTS AND DISCUSSION

In this chapter profile of a hole produced has been studied and effect of process variables i.e. voltage and feed rates on time of machining, taper produced and material removal rate have been discussed. Geometric parameters like taper angle of the hole are also presented.

Reproducibility

Experiments are planned according to the central composite rotatable design for two input parameters. According to the plan 12 experiments are conducted. Out of which 4 experiments have been done under the similar conditions. The tests have been conducted at different point of time. Table 3.1 shows the reproducibility of these experiments. It is clear from the Table 3.1 that the data are reliable.

Sr. No.	V	f (mm/min)	Time (s)	MRR (mg/s)	Taper (^{0})	η (%)
1	22.5	0.65	2340	0.854	0.266	94
2	22.5	0.65	2349	0.848	0.333	100
3	22.5	0.65	2340	0.839	-0.377	97
4	22.5	0.65	2419	0.707	0.644	94

Table 3.1 Reproducibility of the data produced.

3.1 Hole Diameter

It may be recalled that a composite sample, consisting of soldered HSS tool bits, has been machined. The diameter of the hole produced has been measured at different positions with the help of a travelling microscope. Fig 3.1b and 3.1c shows the variation of hole diameter with hole depth. The data points plotted in Fig 3.1b and Fig 3.1c correspond to the diameter measured at positions in the composite sample shown in Fig 3.1a by A, B, C, D and E. The dashed line is indicating outer diameter of electrode (tool or cathode) used. It is observed from the graphs that in most of the cases the hole diameters are coming straight, except in few cases where the diameter at point A is smaller than the intermediate diameter. During all experiments, an initial gap of 0.3 mm is maintained before the start of machining. But during machining, electrode itself maintains an IEG, which is dictated by the operating voltage and tool feed rate. If the initial gap is lesser than equilibrium value then tool does faster machining in the initial stage because of larger current; which might be the reason for initial diameter being lesser than intermediate values.

The equilibrium gap (ye) can be estimated from the following formula[1],

$$y_e = \frac{V\eta\kappa_e E}{\rho_a fF} \quad \text{........................(3.1)}$$

The calculated values of y_e are tabulated in Table 3.2. It is evident from the table that in sample number 1, 2, 6 and 7 the initial gap is smaller than equilibrium gap which makes the tool to machine faster in the initial period till it attains an equilibrium IEG. In samples 1 and 6 the initial gap is close to the equilibrium gap, hence the variation in the diameter at the top and the middle is negligible. This is evident from the Table 3.2 for sample numbers 2 and 7 in which case y_e is much larger than initial gap, hence initial diameters are much larger than intermediate one. In the sample 2 there is large variation in the hole diameter along the entire depth. While machining sample 2, (i) a reduction in the flow rate of electrolyte and (ii) several occurrences of electrode reversal were

observed. These observations are probably due to choking of the hole and could be the possible reason for large variation in the hole diameter.

From the graphs it is also evident that diameter at the bottom of the composite workpiece is smaller than outer diameter of the electrode used. This is due to the fact that once a through hole of sufficient size is formed the entire electrolyte passes through the hole without machining any more. This suspends further machining, and the machining process has to be stopped to avoid any direct contact of oppositely charged electrodes causing short-circuiting.

Both of the negative features namely smaller top and bottom diameters as discussed above, can be obviated with the use of dummy workpieces. The dummy workpieces are soldered both at the bottom and at the top of the actual workpiece (s) which can be removed after the hole is made. It results in a more accurate hole. The assembly of dummy and composite workpieces is shown in Fig 3.2.

Expt. No.	V (volts)	f (mm/min)	y_e (mm)
1	17	0.40	0.35
2	28	0.40	0.57
3	17	0.90	0.15
4	28	0.90	0.25
5	15	0.65	0.18
6	30	0.65	0.37
7	22.5	0.30	0.61
8	22.5	1.00	0.18
9	22.5	0.65	0.28
10	22.5	0.65	0.28
11	22.5	0.65	0.28
12	22.5	0.65	0.28

Table 3.2 Calculated values of inter electrode gap for different conditions.

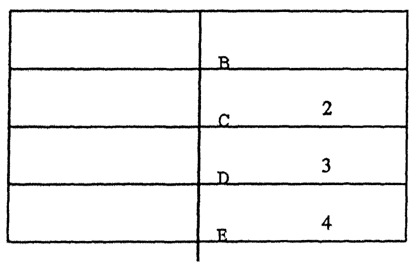


Fig 3.1a The positions A, B, C, D and E on the composite workpiece where hole diameters are measured.

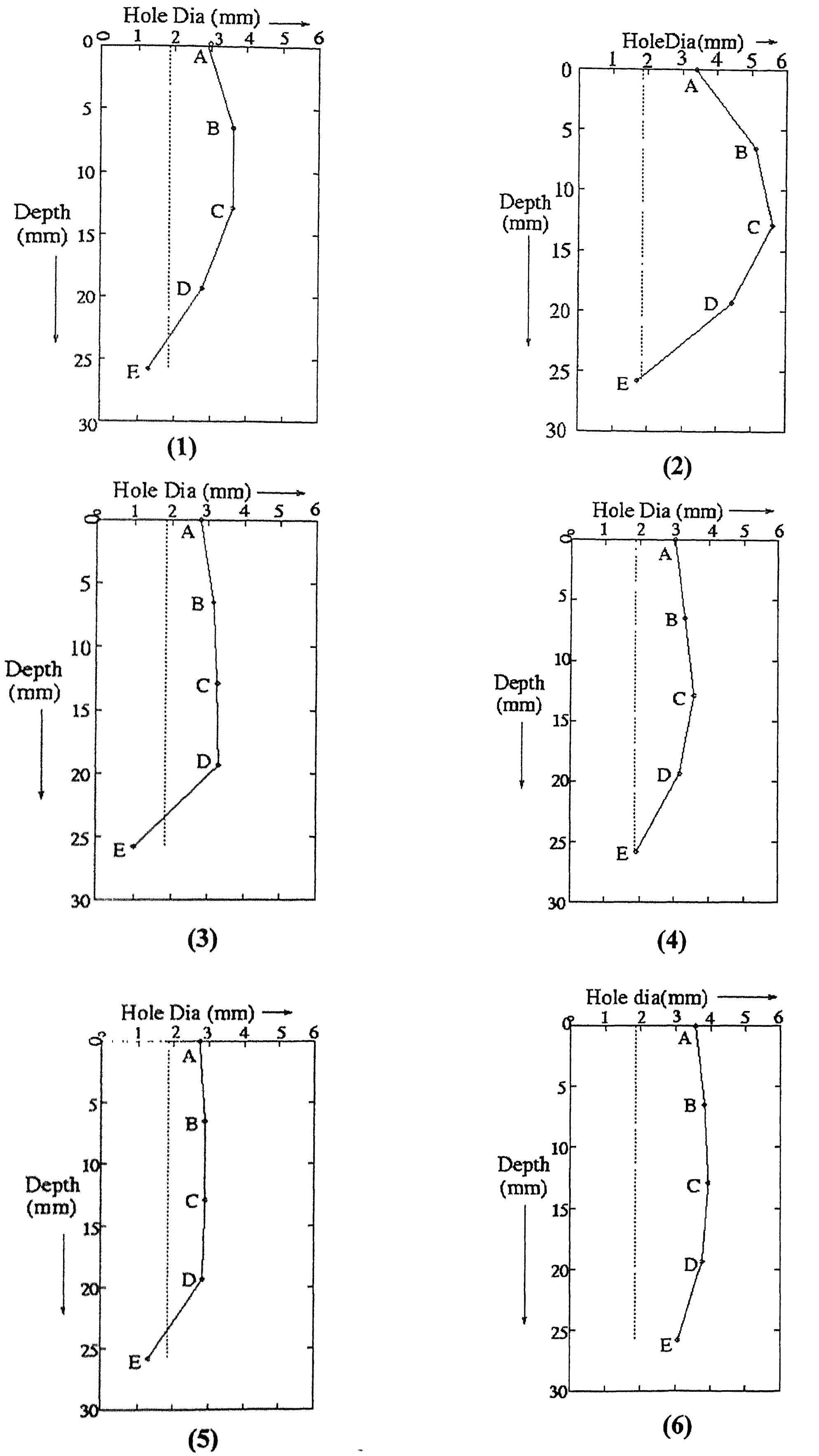
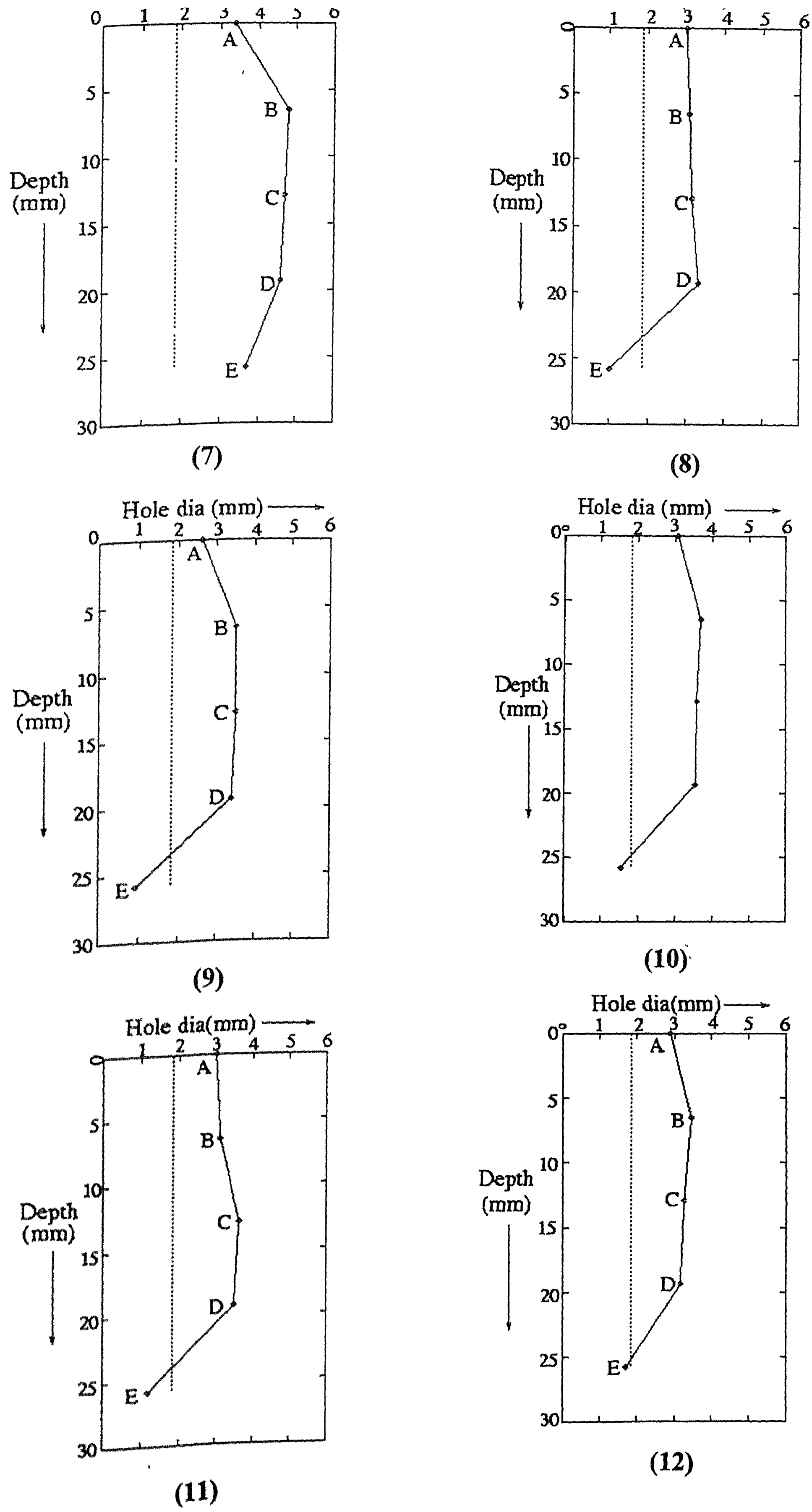


Fig 3.1b The variation in diameter with depth of hole for various samples. (1, 2, 3,...,12 refers to the experiments no. given in Table 3.1)



ABCD

Fig 3.1c The variation of diameter with depth of hole for various samples. (1, 2, 3,…,12 refers to the experiments no. given in Table 3.1)

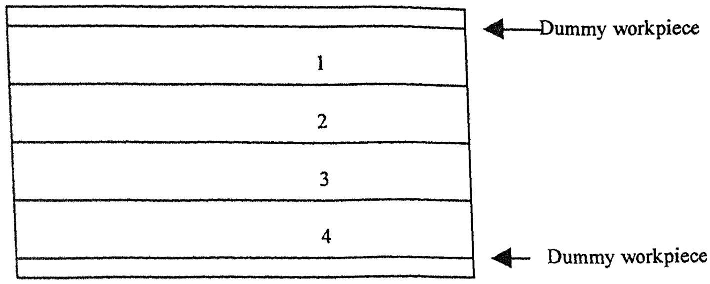


Fig 3.2 The assembly of composite (1, 2, 3 and 4) and dummy workpieces.

3.1.1 Hole contour

The SEM photographs of the hole for samples 5 and 12 at different depths are shown in Figures 3.3 and 3.4 respectively. The corresponding shadowgraphs for those samples are shown in Fig 3.5. From these figures it is evident that these holes are slightly oval in shape and do not have a good surface finish.

If the electrode is not perpendicular to the cathode tool, a non-circular hole will be produced. The reason for the non-perpendicularity is non-perfectly straight (zigzag) electrode. Due to zigzag electrode electrolyte makes a favorable path in particular direction during machining.

The surface finish of the cooling holes has an impact over the rate of cooling of the turbine blades. In the present work, electrochemical machining has been done with NaCl as electrolyte. Studies on iron and nickel have shown that passivating electrolyte such as $NaClO_3$ and $NaNO_3$ give better surface finish than non-passivating electrolytes containing chlorides and bromides[15].

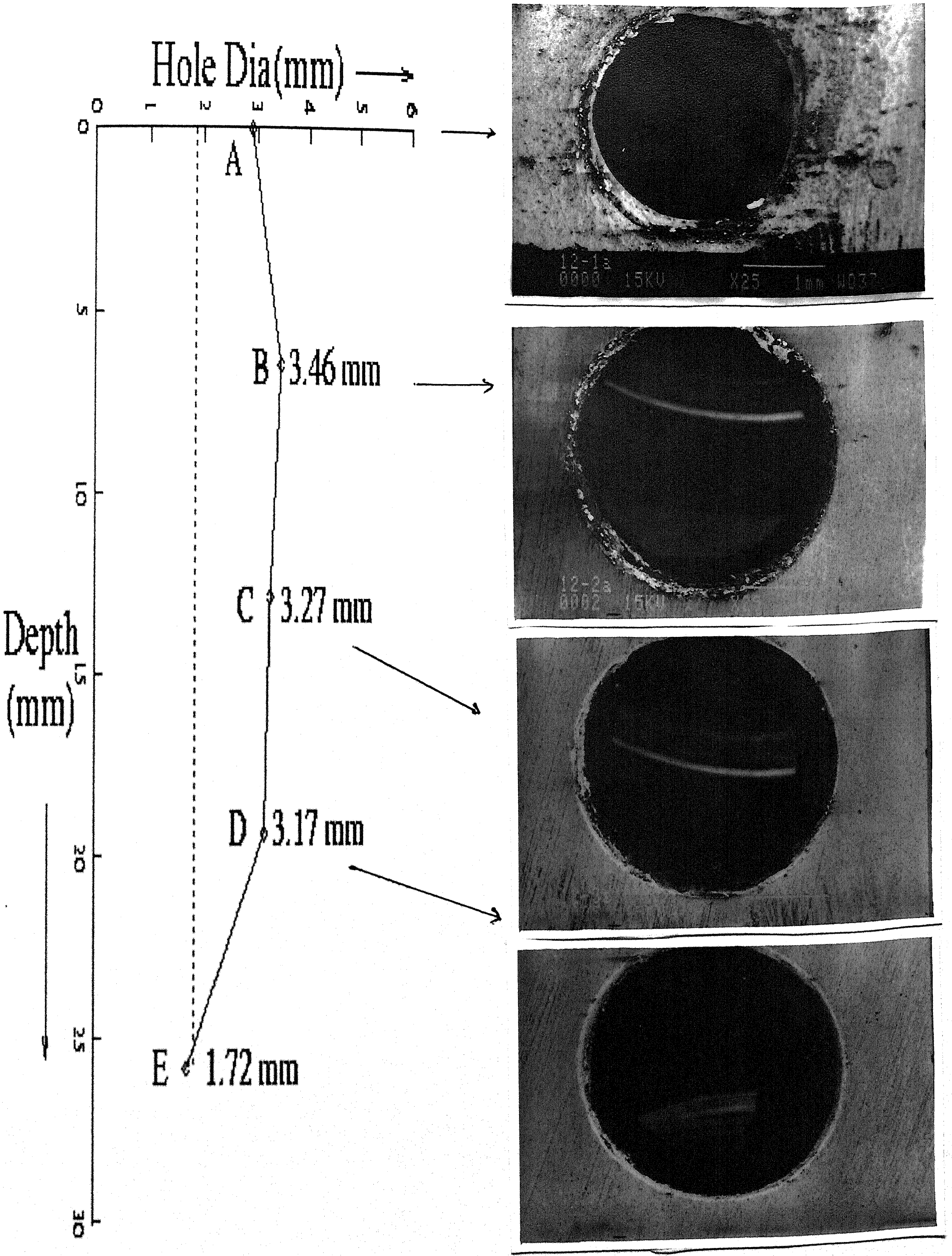


Fig 3.3 SEM photographs of holes at different positions for sample no. 12
(V=15V, feed=0.65 mm/min, Mgnification=25X)

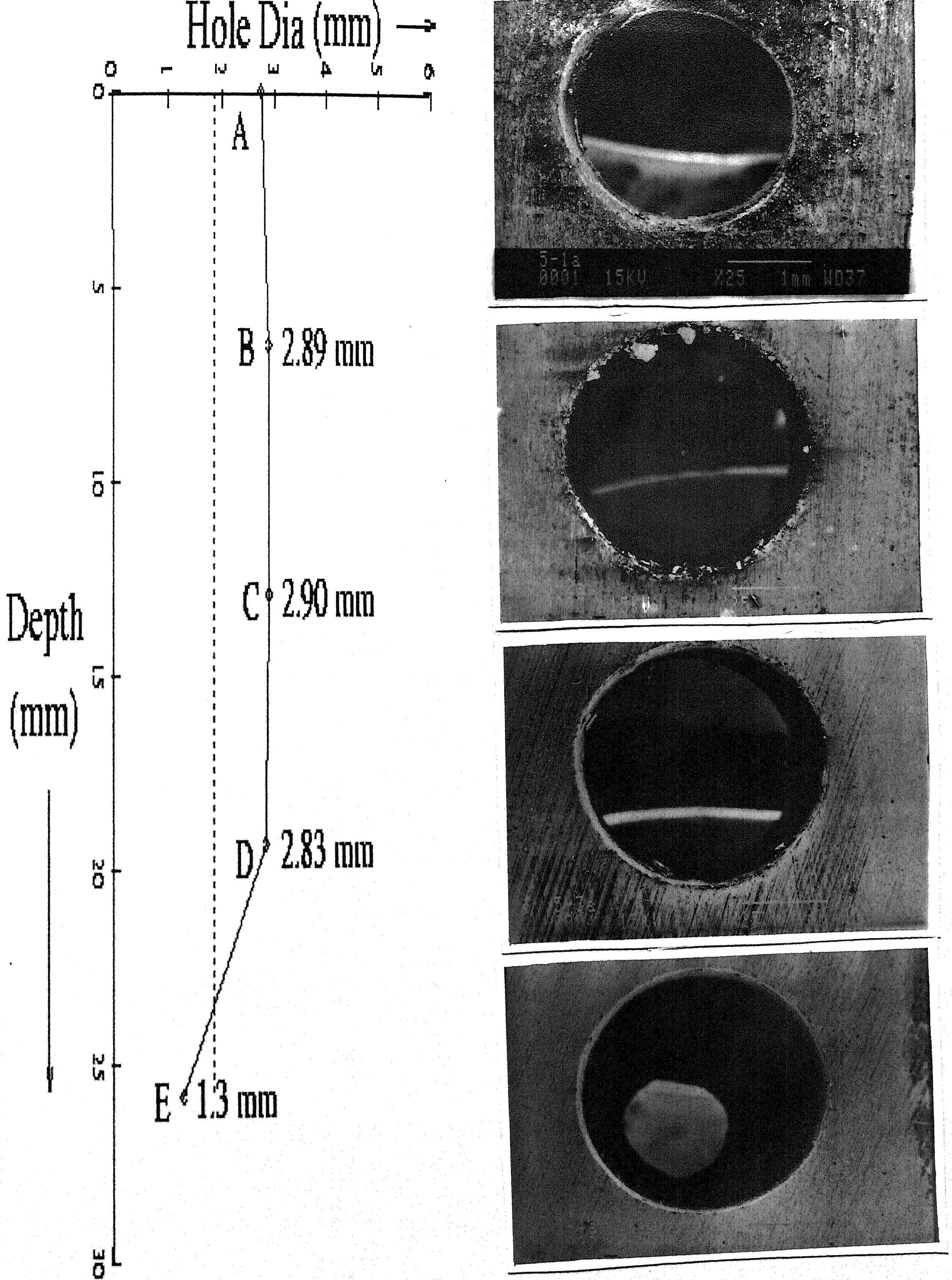


Fig 3.4 SEM photographs of holes at different positions for sample no. 5
(V=15V, feed=0.65 mm/min, Mgnification=25X)

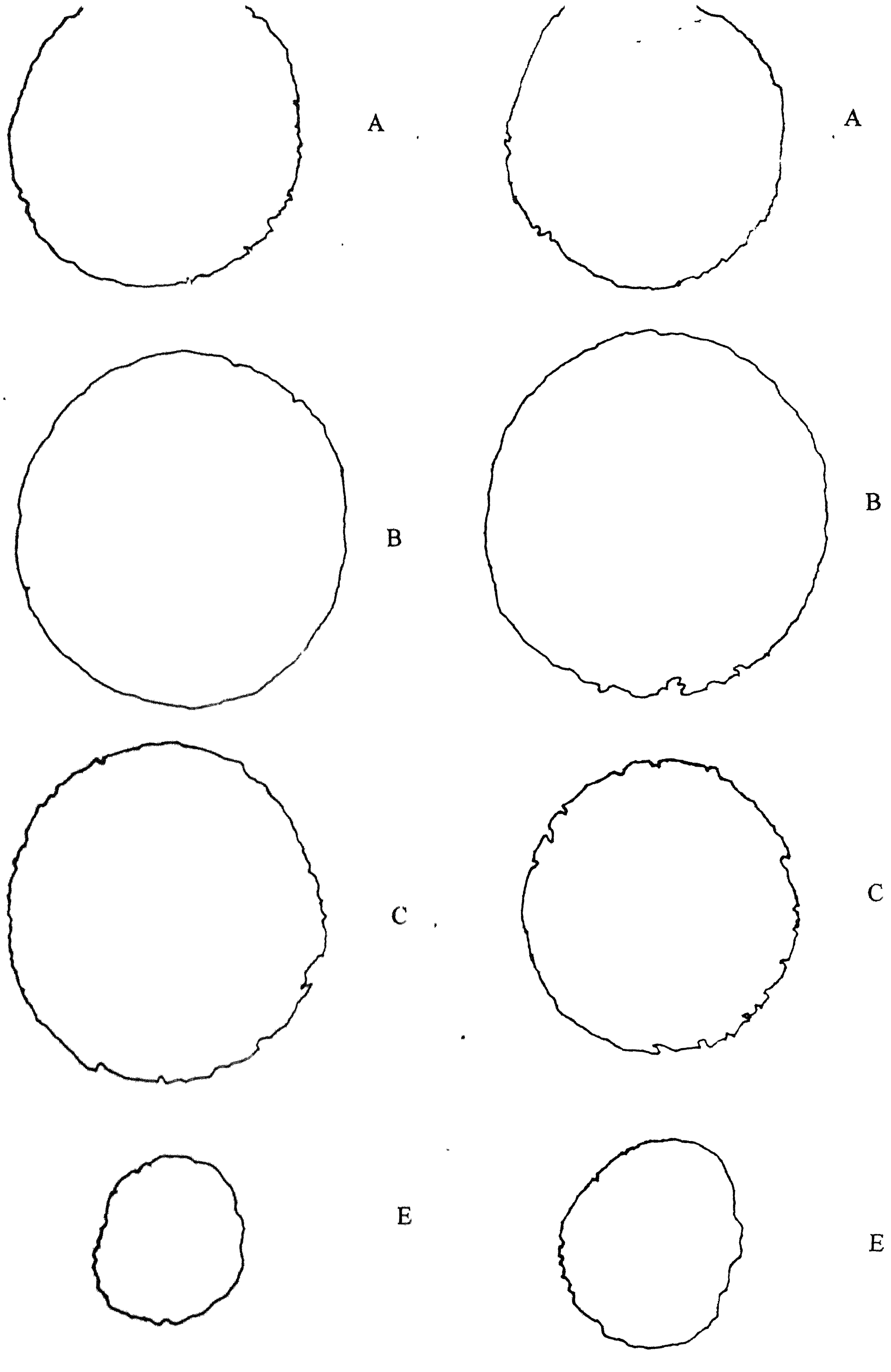


Fig 3.5 Surface contour of the hole produced for sample no 5 and 12 at different positions A, B, C, D.

3.1.2 Overcut

The radial overcut (O_r) is defined as difference in radius of a hole (r_h) and that of the cathode tool (r_t)[1].

$$O_r = (r_h - r_t) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

Table 3.3 gives the extent of radial overcut for different samples. The average diameters are taken into consideration while estimating the overcut. It is observed that in ECM die sinking, overcut is directly proportional to IEG, a similar kind of relationship is observed for the EC drilling except in experiment no. 3. The extent of overcut is mainly governed by stray machining in the sideways. Hence coating on the electrode should be of good quality insulating in nature to curb current flowing sideways.

Expt. No.	**V (volts)**	**f (mm/min)**	**y_e (mm)**	**Radial Overcut (mm)**
1	17	0.40	0.35	0.76
2	28	0.40	0.57	1.61
3	17	0.90	0.15	0.69
4	28	0.90	0.25	0.74
5	15	0.65	0.18	0.51
6	30	0.65	0.37	0.99
7	22.5	0.30	0.61	1.43
8	22.5	1.00	0.18	0.66
9	22.5	0.65	0.28	0.81
10	22.5	0.65	0.28	0.88
11	22.5	0.65	0.28	0.78
12	22.5	0.65	0.28	0.73

Table 3.3 The values of overcut for different samples.

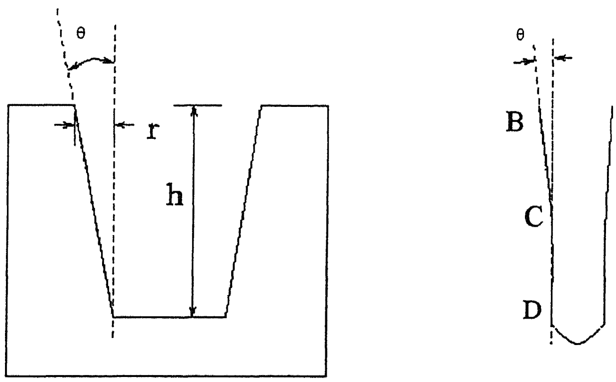
3.2 Taper

In order to assess the quality of the hole produced, its taper angle is estimated.

Taper angle can be calculated from hole profile, using the formula given below,

$$\theta = \tan^{-1}(\frac{r}{h}) \ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

where r and h are shown in Fig 3.6.



(a) (b)

Fig 3.6 (a) Representation of taperness (b) taper angle measurement for actual case. (B, C and D refers to the intermediate points as shown in Fig 3.1a)

The taper angles of the holes produced have been tabulated in Table 3.4. As previously discussed the initial diameter was smaller than intermediate one, and the bottom most diameter was lesser than the electrode diameter. Taper calculated from these values may lead to erroneous results. Hence, the taper has been calculated with average intermediate diameter values.

The insulation, which is used for coating of the electrode, may not be perfectly insulating in nature. Hence, this may lead to very small leakage of current flowing in sideways. Further, if feed rate decreased, the machining time will increase, the top region

of the workpiece will be exposed to the tool for more time. This will result in tapered hole. This might be the reason behind large taper produced in sample 1 than sample 3. Because at a higher feed rates the time required for machining is lesser.

Based on the experimental results, response surface equation to the taper as a function of supply voltage (x1) and feed rate (x2) is given below.

$$Taper = 0.324 - 0.061x_1 - 0.288x_2 + 0.079x_1^2 + 0.229x_2^2 + 0.105x_1x_2 \ldots (3.3)$$

The theoretical taper calculated from the equation 3.3 on the experimental points is also tabulated in Table 3.4. There is somewhat mismatching in the theoretical and the actual values. The parametric analysis has been done, and the effect of voltage on the taper produced for various feed rates is shown in Fig 3.7.

It is observed from the graph that at smaller feed rates, the amount of taper produced is larger. A minima has been observed in taper produced for the feed rates of 0.6 mm/min and 0.8 mm/min. And a minima can be observed in case of feed rate 0.4 mm/min if the curve would have been extended to the larger values of voltages.

Expt. No.	V (volts)	f (mm/min)	Actual Taper (^{0})	Theoretical Taper
1	17	0.40	1.909	1.110
2	28	0.40	1.532	0.762
3	17	0.90	-0.333	0.305
4	28	0.90	0.377	0.399
5	15	0.65	0.133	0.569
6	30	0.65	0.022	0.396
7	22.5	0.30	0.222	1.193
8	22.5	1.00	-0.533	0.376
9	22.5	0.65	0.266	0.324
10	22.5	0.65	0.333	0.324
11	22.5	0.65	-0.377	0.324
12	22.5	0.65	0.644	0.324

Table 3.4 The taper produced for different samples.

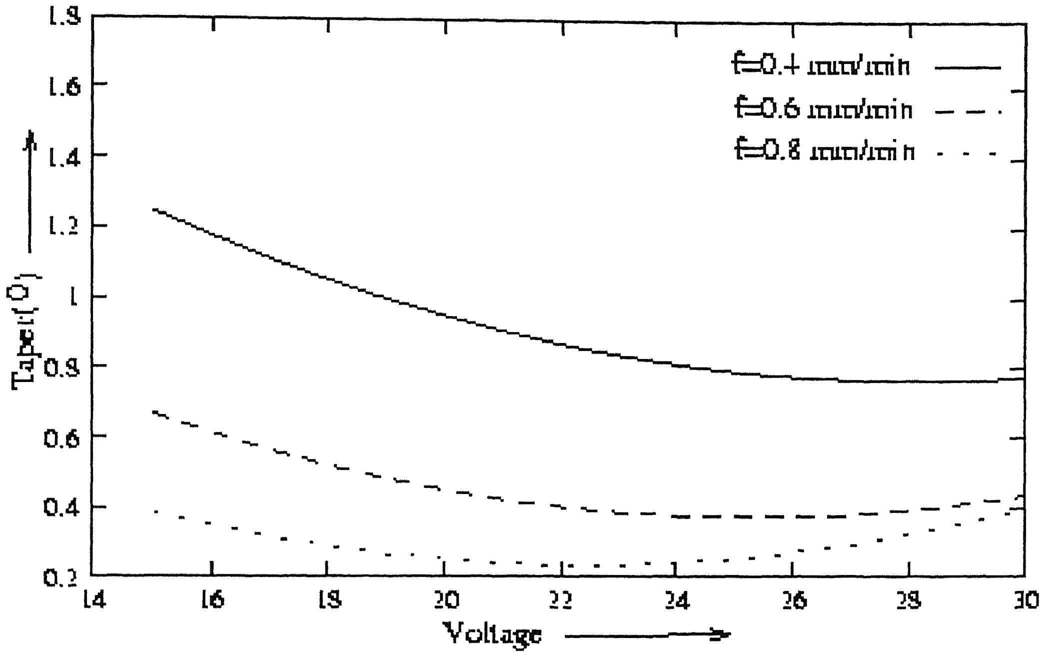


Fig 3.7 The effect of voltage and feed rate on the amount of taper produced.

3.3 Machining Time

The time required for machining is solely governed by tool feed rate provided there are no incidences of electrode reversal. If there are no incidences of electrode reversal then the time of machining is approximately equal to the time required for the tool to move a distance equal to the workpiece thickness to be machined. But in sample 2 and 3 the actual time are larger than calculated time. This may be attributed to the electrode reversals observed during machining.

Based on the experimental results, response surface equation to determine the machining time as a function of supply voltage (x1) and feed rate (x2) is given below.

$$Time = 1890 - 90x_1 - 800x_2 + 199x_1^2 + 572x_2^2 - 148x_1x_2 \text{ ....(3.4)}$$

The comparison of the time of machining by above equation (t_e) and actual one (t_a) is tabulated in Table 3.5. The graph has been plotted for machining time against voltage at different values of feed rates as shown in Fig 3.8. It is clear from the graph that as the feed rate increases the time required for machining decreases. Also as voltage increases the time required increases due to the fact that at higher voltages there are more electrode reversals which increase the machining time.

Expt. No.	**V (volts)**	**F (mm/min)**	**t_a (s)**	**t_e (s)**
1	17	0.40	3000	3063
2	28	0.40	5818	5394
3	17	0.90	2440	2515
4	28	0.90	1847	1267
5	15	0.65	24 27	2271
6	30	0.65	2332	3009
7	22.5	0.30	4770	5028
8	22.5	1.00	1480	1755
9	22.5	0.65	2340	1890
10	22.5	0.65	2349	1890
11	22.5	0.65	2340	1890
12	22.5	0.65	2419	1890

Table 3.5 The comparison of the actual time and the calculated time from the equation 3.3.

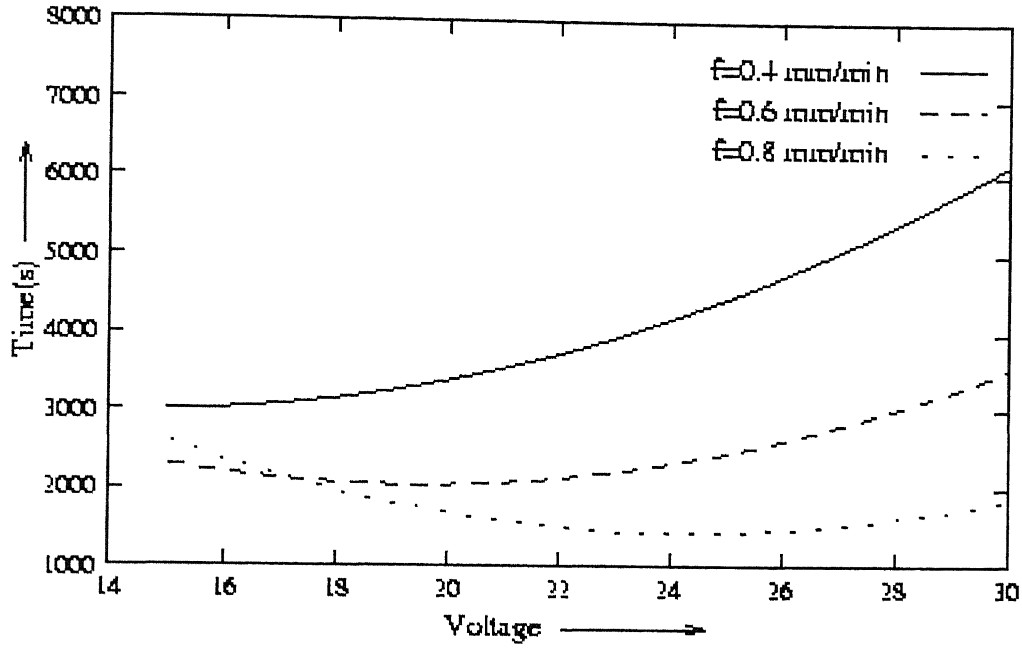


Fig 3.8 The effect of voltage and feed rate on the Machining Time.

3.4 Current Efficiency

The current efficiency (η) is defined as

$$\eta = \frac{\textit{Actual amount of metal removed}}{\textit{Theoretical amount of metal removed}} \quad \ldots\ldots\ldots\ldots\ldots(3.5)$$

The actual amount of metal removed is found by the weight loss of the sample.

Faraday's law states that the amount of metal removed is directly proportional to the amount of current flowing through IEG. Hence, total amount of metal removed can be assessed from the current flowing through IEG. Fig 3.9 shows the variation in the current with machining time. During experimentation, the current was recorded manually after the time interval of five minutes.

The theoretical amount of metal removed can be calculated from Faraday's law.

$$Total\ Metal\ \text{Re}moved = \frac{A}{zF}\sum It \ldots\ldots\ldots\ldots\ldots (3.6)$$

The calculated efficiencies of different samples are tabulated in Table 3.6. It is observed from the Table 3.6 that in most of the cases calculated metal removed are in good agreement with theoretical amount of metal removed. Some inaccuracy may result from the current measurement from the fact that the resolution of the ammeter was 1 Amp. For accurate estimation of the efficiency of machining the current should be recorded continuously.

In most of the cases current efficiency is close to 100% which is the case with NaCl electrolyte. This indicates that there is no side reactions taking place during machining. But there are some cases where efficiencies are coming more than 100%, this is due to (a) measured current values are not perfectly correct and (b) error in the assumption of the valence state of metal dissolution. Also, in NaCl electrolyte there is no formation of passive layer which can hinder the machining rate[6].

From the experimental results, a response surface curve has been obtained:

$$MRR_g = 0.649 + 0.089x_1 + 0.124x_2 + 0.032{x_1}^2 + 0.078{x_2}^2 + 0.029x_1x_2 \ldots (3.7$$

To study the effect of voltage and feed rate the graph (Fig 3.10) has been plotted for MRR_g against the voltage at different tool feed rates. It is evident from the graph that as the feed rate increases, the MRR_g increases. MRR_g also increases with increase in voltage. This is basically due to the fact that as the voltage increases the amount of current increases resulting in higher MRR_g. These leads to a larger diameter hole

Expt. No.	V (volts)	f (mm/min)	W_a (g)	MRR_g (mg/s)	W_t (g)	η (%)
1	17	0.40	1.768	0.589	1.719	102
2	28	0.40	3.33	1.12	*	*
3	17	0.90	1.762	0.722	1.934	91
4	28	0.90	1.645	0.891	1.805	91
5	15	0.65	1.427	0.588	1.504	94
6	30	0.65	2.192	0.939	2.406	91
7	22.5	0.30	3.055	0.640	2.920	104
8	22.5	1.00	1.582	1.098	1.460	108
9	22.5	0.65	1.999	0.854	2.110	94
10	22.5	0.65	1.994	0.848	1.980	100
11	22.5	0.65	1.964	0.839	2.020	97
12	22.5	0.65	1.712	0.707	1.810	94

Table 3.6 The values of efficiency calculated for different samples. (W_a indicates actual weight loss and W_t calculated weight loss)

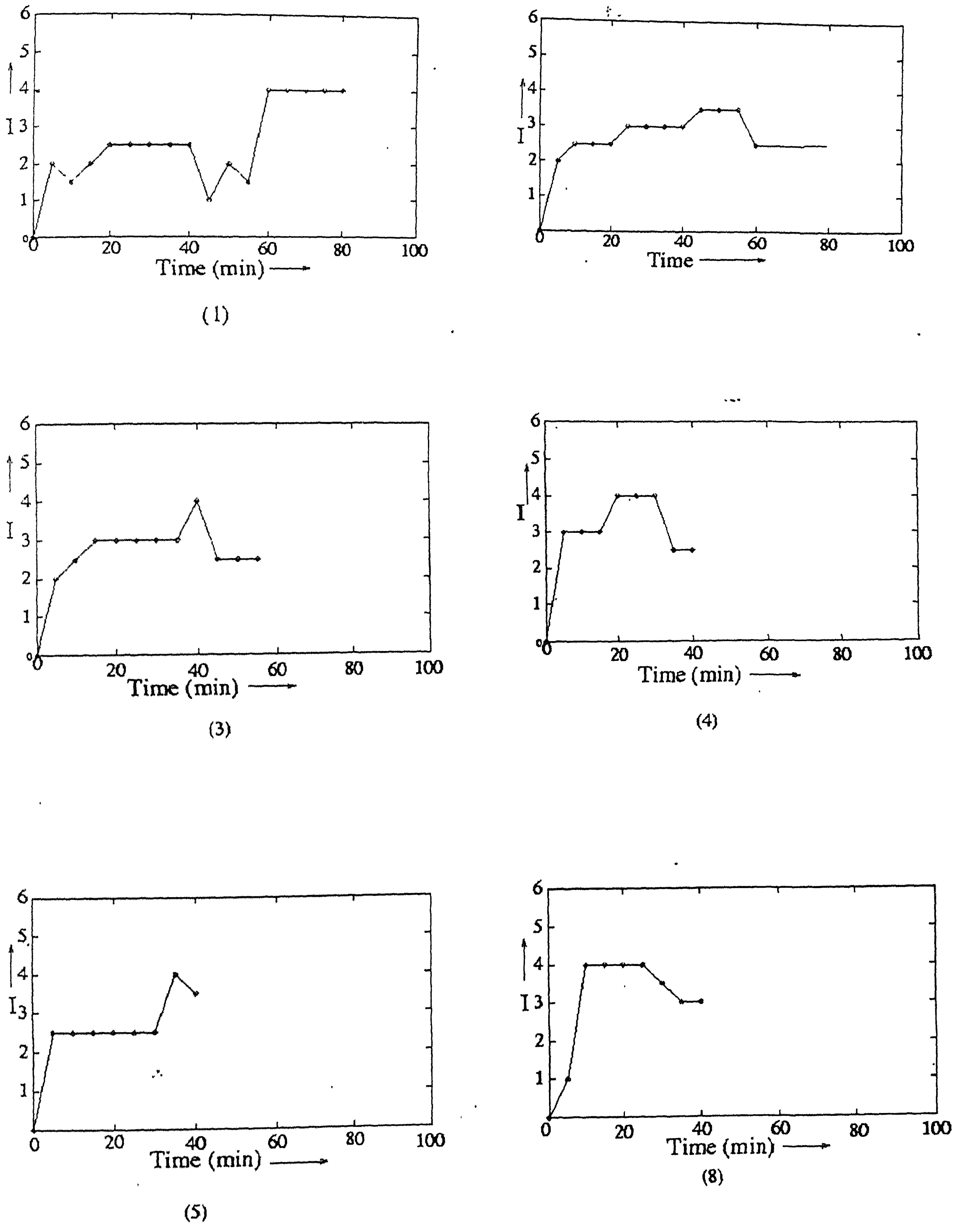


Fig 3.7 Current variation during machining for different samples.

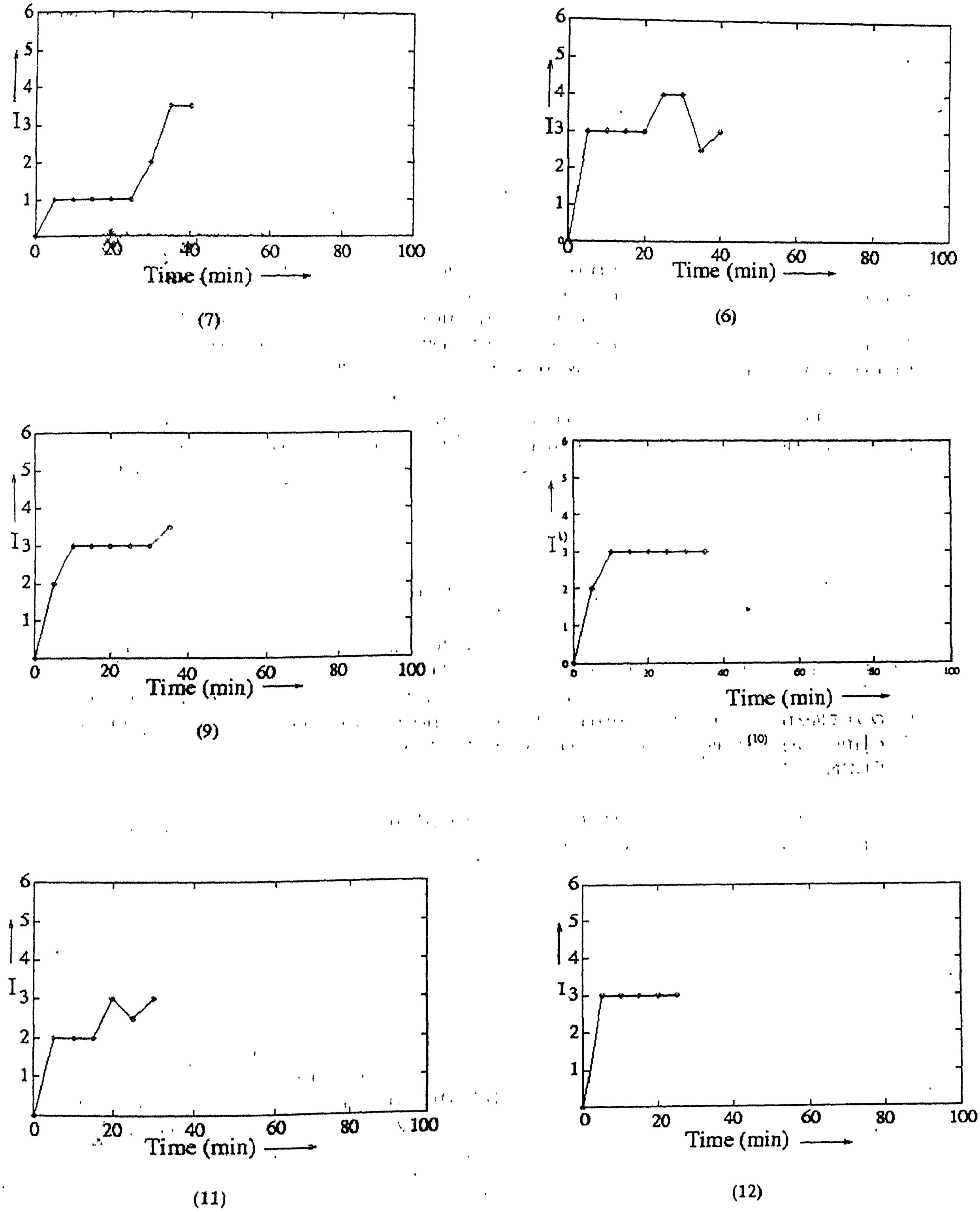


Fig 3.7 Current variation during machining for different samples.

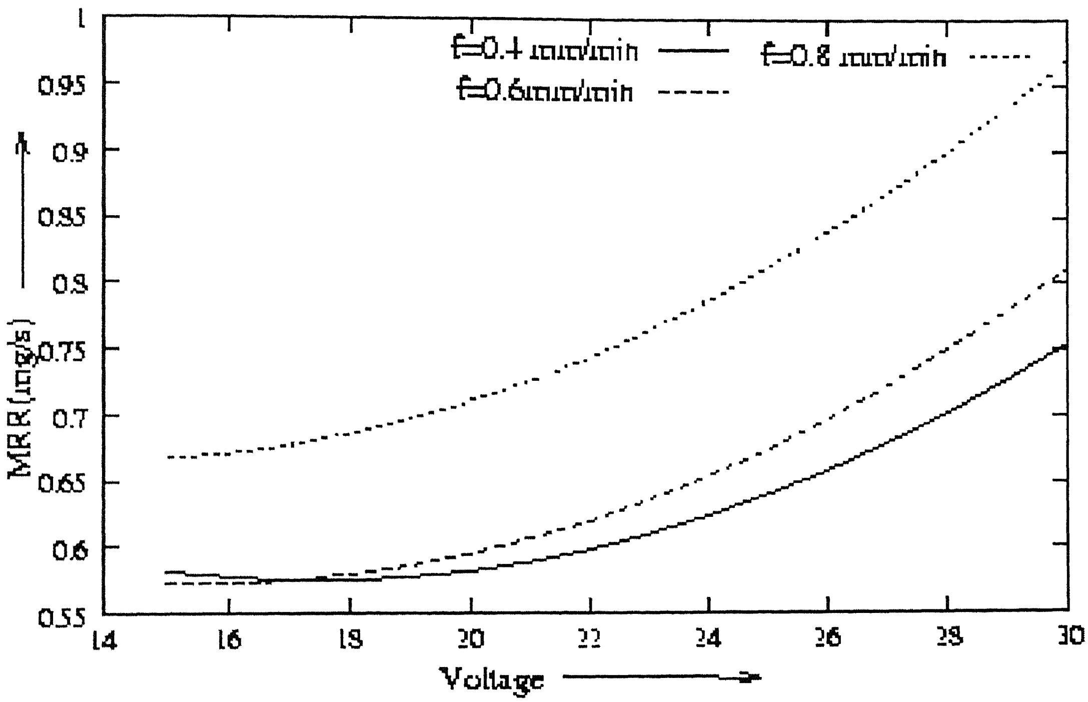


Fig 3.10 The effect of voltage and feed rate on MRR.

3.5 Experiments on Inconel

Inconel is a superalloy of composition 16 % Cr, 8% Fe and Ni. Inconel is difficult to machine alloy, hence non-traditional machining methods are needed for machining Inconel.

Few experiments have been conducted on Inconel under the best possible conditions coming out of results of machining of HSS. The results coming from experiments on Inconel are presented in Table 3.7. It is observed from Table 3.6 that the time required for machining is more than that in case of machining in Inconel. Also, the current efficiency was found to be quite lesser than HSS (100%). The photograph of the hole drilled in Inconel is shown in Fig 3.11.

Expt. No.	V (volts)	f (mm/min)	Taper (^{0})	Time (sec)	MRR (mg/s)	η (%)	d_{min} (mm)	d_{max} (mm)	Aspect Ratio
1	22.5	1.00	-0.382	2820	0.816	63	3.70	3.90	8
2	17	1.00	0.02	2640	0.534	78	2.69	2.68	11
3	15	0.65	-0.534	3300	0.442	52	2.95	3.23	10

Table 3.7 The experimental results on Inconel alloy.

Ni has very superior corrosion resistance properties. It is very stable in seawater, non-oxidizing acid and alkalis. The corrosion resistance of Ni increases with addition of Cr[16]. Hence Inconel is more resistant than HSS, which contains iron in large amount. Ni forms an oxide layer on to the surface to resist corrosion. But Cl- ion is very aggressive in nature, it attacks this film. This result in relatively porous film on the surface. This might be the reason behind low rate of metal dissolution of Inconel as compared to HSS. Hence the resistance of the IEG is more. This makes the tool to maintain a smaller IEG to pursue faster machining so that MRR_l matches with feed rate.

Following observations have been made during the experimentation on Inconel.

1. The flow rate of electrolyte was found to be lesser than in case of HSS. This is mainly due to smaller IEG.
2. The time required for machining was more for the corresponding case in HSS machining. This is due to incidences of electrode reversals. Since the inter electrode gap is smaller, a slight accumulation of the sludge will make the chances of short circuiting brighter.
3. The current efficiency of the metal dissolution is lesser than that in case of HSS. This might be due to formation of oxide film on the surface, which hinders the removal of metal.

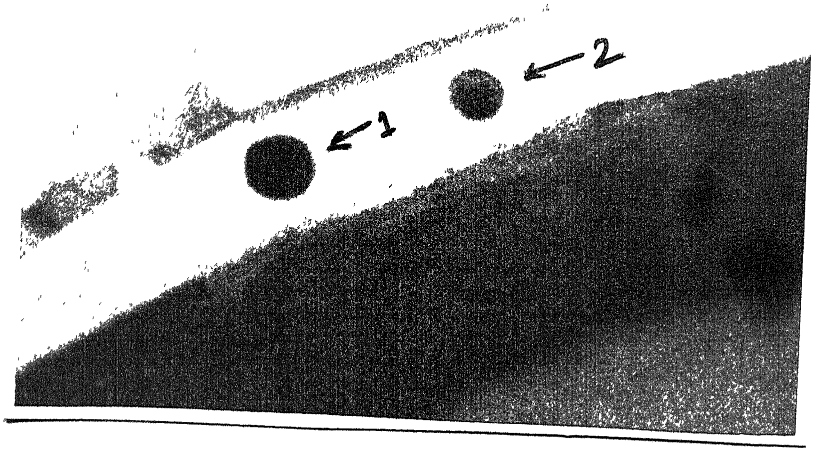


Fig 3.11 Photograph of the hole produced in Inconel from experiment number 1 and 2.

Chapter 4

Conclusions And Scope For The Future Work

4.1 Conclusions

1. With the achievement of an aspect ratios of the order of 10, it seems hopeful to achieve even higher aspect ratios with this method.

2. With the use of smaller diameter electrodes and some modification in experimental condition it seems feasible to drill smaller diameter holes.

3. The experimental results on HSS shown that larger feed rates than 1.00 mm/min can be used without any danger of sparking when NaCl is being used.

4. As the voltage increases, the extent of overcut and taper increases, while increase in the feed rate leads to decrease in overcut and taperness.

5. The holes produced are slightly in shape due to non straight tool. Round holes can be produced with the straight and rotating tool.

6. The current efficiency is coming around 100% in case of HSS. While in case of Inconel the efficiency of dissolution was found to be smaller.

7. The bottom diameter is smaller than the tool diameter due to the reason stated in previous section. This problem can be solved with the use of dummy workpiece.

4.2 Scope For The Future Work

- The electrolyte flow condition between the gap affects the finish of the surface produced; hence this can be a useful area of further research work.

- Since after each experiments the pH and conductivity of the solution changes, this can affect the rate of material dissolution. Hence, the effect of re-circulation of the electrolyte can be studied. It will be of great help in designing of the electrolyte system for ECM machine.

- The passivating nature of metal changes with electrolyte, there is no single electrolyte, which can be used for all purposes. Passivation plays a key role in the resulting tolerances of the part produced. The selection of a suitable electrolyte for a particular metal can be a strong area of work.

- The length of bare portion has an effect on the amount of overcut, hence that is the prominent area of research.

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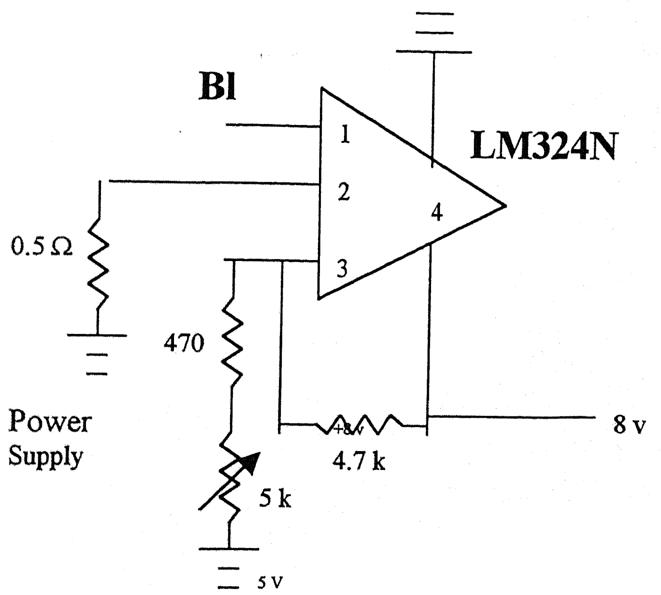

Fig A1 Electrical circuit for sensing the current.

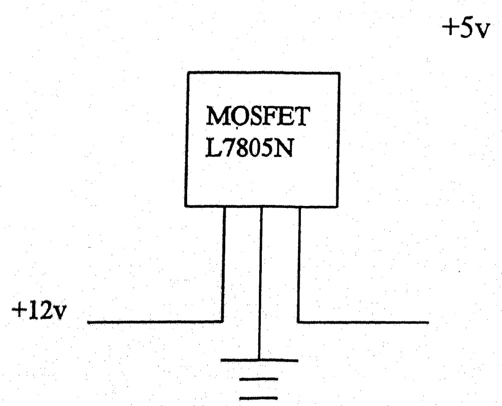

Fig A2 Converter from 12v to 5v DC.